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INFRA-RED PHOTOMETRY OF RED GIANTS IN THE GLOBULAR CLUSTERS 47 TUC AND ω CEN

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SUMMARY

J, H, K, L (1·25–3·5 μ) photometry and some spectral types are given for red giants (including variables) in 47 Tuc and ω Cen. Bolometric corrections were derived for those stars which also have U, B, V, R, I photometry (from Eggen). These bolometric corrections are close to those for Population I giants of the same colours. For both clusters the relations between the various colours (and between the colours and TiO spectral types) are similar to those for Population I giants. The excess in the H band (probably mainly an H^- opacity minimum) is found in all stars including the ω Cen M type variables but excluding the three Miras in 47 Tuc. The photometry of the ω Cen M type variables confirms that they are cool objects (log $T_{\rm eff} \sim 3{\cdot}50$). These variables have considerable ($\sim 0^{\rm m}{\cdot}4$), (U–B) excesses for their types and infra-red colours, presumably due to metal deficiency. The TiO bands are as strong in these stars as in Population I giants of the same infra-red colours. This probably indicates that TiO is itself an important source of opacity in these stars. These stars probably represent an early stage in the rapid evolution from the top of the asymptotic giant branch. There is evidence for a small 3·5 μ (L) excess in 47 Tuc V3, and possibly also in ω Cen V6.

1. INTRODUCTION AND OBSERVATIONS

During recent years a great deal of effort has been devoted to photometry in the infra-red of a wide variety of stars. Work by Brooke (1969) and Eggen (1972) has shown the usefulness of near infra-red (R, I) photoelectric photometry for the study of globular clusters whilst Dickens, Feast & Lloyd Evans (1972) have shown that interesting results may be obtained photographically in this wavelength region. However there has been little or no work on globular cluster stars (or indeed on halo type stars in general) in the further infra-red. The present paper reports J, H, K, L (1·25, 1·65, 2·2 and 3·5 μ) observations of some red giants in the metal-rich globular cluster 47 Tuc and in the metal-poor globular cluster ω Cen. The following were some of our aims in carrying out this programme.

(1) *To determine bolometric corrections*

For typical red giants in this study more than half of the energy of the star is radiated beyond 1 μ where there have previously been no direct measurements. The bolometric corrections generally employed were determined for field (Population I) stars (Johnson 1966; Lee 1970) and it seemed very desirable that the applicability of these corrections to globular cluster stars be confirmed observationally.

(2) *To study red giant variables*

We were particularly interested in studying further some of the variables with strong TiO absorption which have recently been found to be members of ω Cen and if possible obtaining clues to the temperatures and chemical compositions of these stars.

(3) *To investigate generally the usefulness of infra-red work in the study of globular clusters*

As regards this last point, the present work may be considered as a pilot project for a possible larger scale study.

The observations were made in June and September 1972 with an infra-red photometer (Glass 1973, in preparation) mounted at the Cassegrain focus of the Radcliffe 74-in. (1·88-m) reflector. The results are listed in Table I. Standard stars were selected from the photometry of Johnson *et al.* (1966) and from Hyades photometry (Iriarte Erro 1970). The standard error of a single measure in *J*, *H* or *K* is $0^m{\cdot}08$ and in *L* it is $0^m{\cdot}20$. In the case of ω Cen there is a zero point uncertainty in *L* which may amount to $\sim 0^m{\cdot}2$. Table II gives previously unpublished spectral types for some of the stars observed. These were derived from 140 A mm^{-1} spectra taken with the Cassegrain grating spectrograph and RCA two stage cascade phosphor image intensifier on the 74-in. telescope. They depend on estimates of the TiO band strength.

2. BOLOMETRIC CORRECTIONS

For a number of the stars in Table I, Eggen (1972) has published *U*, *B*, *V*, *R*, *I* photometry. For these stars the spectral energy distributions were integrated to determine the bolometric corrections. The photometry was corrected for a reddening $E_{B-V} = +0{\cdot}03$ for 47 Tuc and $E_{B-V} = +0{\cdot}11$ for ω Cen (*cf.* Eggen 1972). Corresponding reddening corrections at other wavelengths were made assuming reddening according to van de Hulst's curve 15 (*cf.* Johnson 1968). Table III shows the absolute flux calibration which was used (Becklin, private communication). It differs only slightly from that of Johnson (1966). Unless the stars are very abnormal only a very small amount of energy is contributed at wavelengths shorter than 0·36 μ (*U*). A correction was applied for the contribution of the unobserved region beyond 3·5 μ (or in two cases without *L* measures, beyond 2·2 μ). This correction assumes that the long wavelength tail follows the results for late type giants given by Johnson (1966). The corrections are quite small (~5 per cent of the total energy when the measures include *L* (3·5 μ) and ~15 per cent when they extend only to *K* (2·2 μ)).

For the small range variables mean values of the photometry were adopted. No attempt was made to determine bolometric corrections for the large range (Mira) variables in 47 Tuc for which simultaneous photometry at all wavelengths is clearly necessary.

Eggen (1969) noted that Johnson's (1966) bolometric corrections for field Population I stars are well represented by the relation B.C. = 1 − (*V*–*I*) over a rather wide range of temperatures. Column 3 of Table IV shows the differences between the directly measured bolometric corrections and the ones derived in this latter manner. For the 47 Tuc stars and the non-variable stars in ω Cen (actually some of these stars are very small amplitude variables, *cf.* Cannon & Stobie 1973)

TABLE I

Infra-red photometry

(a) 47 Tuc

Star	*J*	*H*	*K*	*L*	No. of observations or date (1972)
R10	8·32	7·46	7·27	7·21	3
R17	8·75	7·86	7·66	7·63	3
R18	8·45	7·56	7·44	7·15	2
R23	8·69	7·78	7·57	7·47	2
R26	8·48	7·55	7·34	7·24	3
R32	10·63	10·02	9·81	—	1
R36	8·80	7·85	7·64	7·40	3
W3	9·20	8·19	8·09	7·75	2
W12a	8·56	7·71	7·55	7·29	2
W76	8·98	8·18	7·99	7·87	2
W77	9·38	8·53	8·34	—	3
W78	9·43	8·55	8·48	—	3
W81	8·51	7·60	7·41	7·34	2
W300	8·39	7·53	7·34	7·04	1
A8	8·79	7·87	7·68	7·55	3
V1	7·25	6·40	6·08	5·69	6 June
V2	7·90	7·11	6·73	6·33	6 June
	7·17	6·32	6·00	5·63	9 Sept
V3	7·31	6·54	6·28	5·68	6 June
	7·53	6·78	6·42	5·89	29 June
	7·65	6·79	6·40	5·85	9 Sept
	7·49	6·73	6·33	5·75	26 Sept
V5	8·57	7·68	7·48	7·25	3
V6	8·51	7·57	7·40	7·23	1
V7	8·21	7·28	7·02	6·76	3
V11	7·92	6·97	6·74	6·44	2

(b) ω Cen

Star	*J*	*H*	*K*	*L*	No. of observations or date (1972)
RGO 40	8·76	8·00	7·87	7·93	1
RGO 43	8·67	7·88	7·67	7·86	1
RGO 56	8·82	7·95	7·84	7·94	1
RGO 66	8·70	7·86	7·72	7·74	1
V6	8·57	7·58	7·30	6·89	6 June
V17	8·71	7·80	7·57	7·67	4 June
	8·94	7·93	7·76	7·54	6 June
	8·72	7·77	7·54	7·55	27 June
V53	9·18	8·35	8·17	8·10	1
V138	8·70	7·93	7·82	7·61	1
V148	8·81	8·02	7·90	7·62	2
V162	8·98	8·22	8·06	8·21	1
V164	9·24	8·28	8·22	8·16	1

Notes

47 Tuc

Stars are denoted by their R (Feast & Thackeray 1960), W (Wildey 1961) or variable star designations (*cf.* Sawyer Hogg 1973). W12a is the star ~0′·3 South of W12 (note that W12 = V11). A8 is a small amplitude variable identified by Lloyd Evans & Menzies (1973).

ω Cen

Stars are denoted by their RGO (*Royal Observatory Annals* No. 2, 1966) or variable star designations.

Table II

New spectroscopic data

Star	Plate	Date	Type
		47 Tuc	
R17	CX263C1	23.7.71	M1–2
R18	CX263C1	23.7.71	M2–3
R23	CX263C1	23.7.71	M2
A8	CX592C1	16.9.72	M1–2
W12a	CX592C1	16.9.72	M2–3
W76	CX687C1	2.2.73	M0 or 1
W77	CX687C1	2.2.73	M0:
W78	CX687C1	2.2.73	M0 (or earlier, TiO bands marginal)
W81	CX687C1	2.2.73	M2–3
W300	CX687C1	2.2.73	M3:
V1	CX503C1	16.6.72	M4–5
V2	CX503C1	16.6.72	M4:
V6	CX592C1	16.9.72	M0–1
V11	CX592C1	16.9.72	M4
		ω Cen	
V6	CX502C1	16.6.72	M4
V17	CX468C1	6.4.72	M4
	CX498C1	13.5.72	M4
	CX502C1	16.6.72	M4
	CX513C1	8.7.72	M3
	CX560C1	13.8.72	M4
RGO 320	CX499C1	13.5.72	M2
	CX513C1	8.7.72	M2

the agreement between the two determinations is obviously very good. For the ω Cen variables the bolometric luminosities directly determined are ~ 14 per cent higher. Near simultaneous photometry at all wavelengths is needed to check this point. Our results indicate that the bolometric correction derived for Population I stars apply also to red giants in metal-poor and metal-rich globular clusters.

3. DISCUSSION OF THE 47 TUC RESULTS

Fig. 1 shows the relation between $(J–K)_0$ and spectral type for 47 Tuc. Spectral types not given in Table II were taken from Feast & Thackeray (1960). The lines are the relations for field Population I stars of luminosity classes I and III (Lee 1970). The agreement between the points and the Population I relations is adequate taking into account likely errors in the spectral types and photometry. It may be particularly noticed that there is good agreement with the Population I relation for the two Mira variables (V1 and V2) where the spectral types were determined within a few days of the photometry (compare dates in Tables I and II). An apparently discrepant point is R10. This was classed as K3II by Feast & Thackeray (1960) using atomic line strengths and TiO bands are not evident. The star is found to be variable (Lloyd Evans & Menzies 1973).

Fig. 2 shows the $(R–I)_0$, $(J–K)_0$ relation for those stars in the present work for which Eggen (1972) has given $(R–I)$ measures (here as throughout Eggen's original measures on the Kron system have been converted to the Johnson system

TABLE III

Adopted absolute flux calibration (after Becklin)

	$\lambda(\mu)$	f_λ W cm^{-2} μ^{-1}		$\lambda(\mu)$	f_λ W cm^{-2} μ^{-1}
U	0·36	$4\cdot35\times10^{-12}$	*H*	1·65	$1\cdot16\times10^{-13}$
B	0·43	$7\cdot20\times10^{-12}$	*K*	2·2	$4\cdot0\times10^{-14}$
V	0·54	$3\cdot92\times10^{-12}$	*L*	3·5	$7\cdot3\times10^{-15}$
R	0·70	$1\cdot76\times10^{-12}$	*M*	4·8	$2\cdot5\times10^{-15}$
I	0·90	$8\cdot3\times10^{-13}$	*N*	10·1	$1\cdot23\times10^{-12}$
J	1·25	$3\cdot4\times10^{-13}$			

using relations that Eggen gives). Fig. 2 also shows the blackbody line and the calibration for luminosity class III stars of Population I by Lee (1970) and (for stars earlier than Mo) by Johnson (1966). The agreement of the points with this calibration (which is itself quite close to the blackbody line) is good.

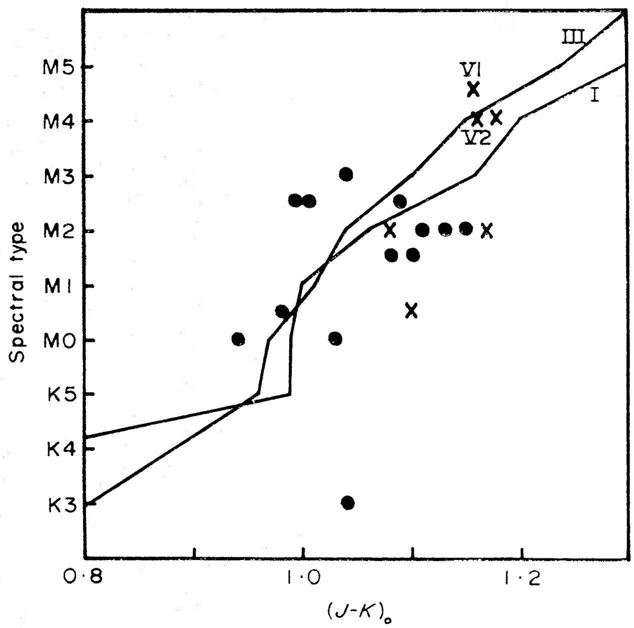

FIG. 1. *Relation between spectral type derived from TiO bands and* $(J\text{–}K)_0$ *for 47 Tuc stars. For coding see Fig. 2. The mean relations for Population I, luminosity class I and III stars are shown.*

Fig. 3 shows the $(J\text{–}H)_0$, $(H\text{–}K)_0$ diagram together with the blackbody line and the calibration for Population I field M stars by Lee (1970). It has been known for some years (e.g. Woolf, Schwarzschild & Rose 1964; McCammon, Munch & Neugebauer 1967; Bahng 1969) that the H band (1·65 μ) coincides with a continuum peak in late type Population I stars and that this explains their departure (as in Lee's calibration) from the blackbody line. This continuum peak is probably due to the occurrence of an opacity minimum at this wavelength (*cf.* Woolf *et al.* 1964 etc.). The opacity due to bound-free transitions of H^- increases at shorter wavelengths and that due to free-free transitions of H^- increases at longer wavelengths. Consider first the non-variable and small amplitude stars (i.e. omitting the three Mira variables V1, V2, V3). We also omit from discussion R32 which falls away from the other 47 Tuc points in Fig. 3. This star is considerably fainter than others in the programme and further confirmation of its photometry is desirable. It is evident that, the Mira variables and R32 apart, the 47 Tuc stars are displaced from the blackbody line in a similar manner to the Population I stars. There is a suggestion that in the mean the 47 Tuc stars are somewhat more displaced than the Population I giants. This requires confirmation with more extensive photometry. It might imply that other forms of opacity are less important relative to H^- in the 47 Tuc stars than in the Population I stars.

Perhaps the most striking feature of Fig. 3 is the position of the three 47 Tuc Mira variables (V1, V2 and V3) which lie much closer than the other stars to the blackbody line at the epoch at which they were observed. The possibility that this displacement is due to an excess of radiation in the K (2·2 μ) band can be dis-

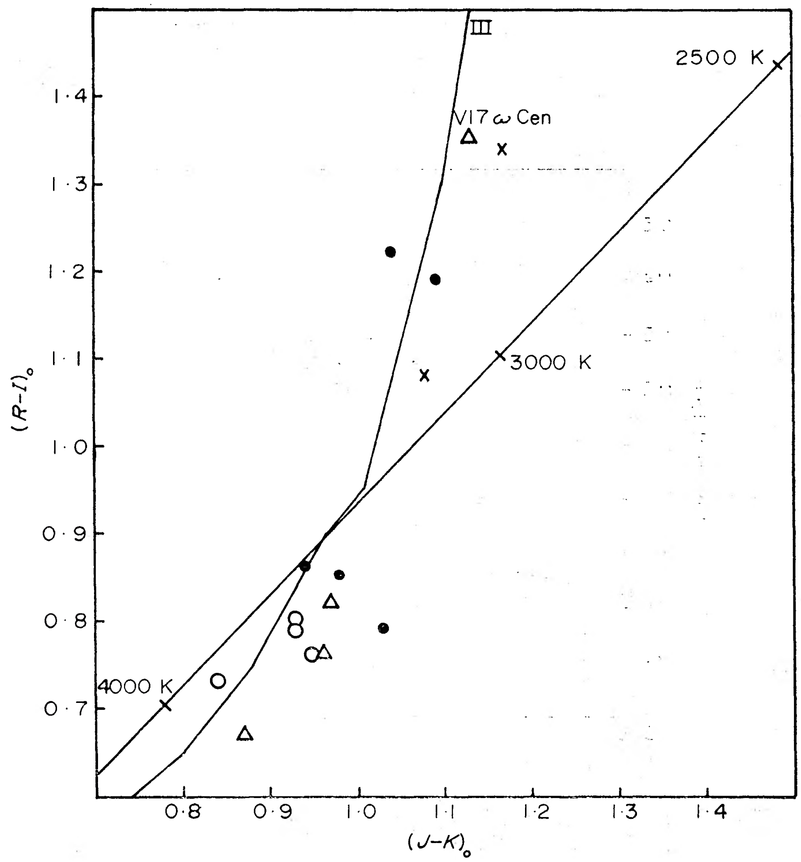

FIG. 2. $(R-I)_0$, $(J-K)_0$ *relation for ω Cen and 47 Tuc stars. The (straight) blackbody line and the mean relation for Population I luminosity class III stars are shown. Filled circles, 47 Tuc stars; crosses, 47 Tuc variables with ' V ' designations in Table I(a); open circles, ω Cen stars; open triangles, ω Cen variables with ' V ' designations in Table I(b).*

counted because of the good agreement for two of these stars (V1 and V2) with the Population I M-giant calibration in the spectral type—$(J-K)_0$ diagram (Fig. 1). The effect must be due to a decrease in the H band radiation excess. The star is thus moved diagonally down from left to right in Fig. 3. Unfortunately rather few measurements of field Mira variables have been made in the H band (1·65 μ) and none of the Miras measured have periods as short as the ones in 47 Tuc ($\sim$200 days). The available data (Mendoza 1967) are plotted in Fig. 3 using lens-shaped symbols (in the case of T Cas reddening corrections corresponding to E_{B-V} = 0·3 have been applied, following Mendoza). As can be seen the long period Miras are in general too cool for a comparison to be made with the 47 Tuc stars.

However, as shown, some field Miras (e.g. R Peg, o-Ceti) do pass through the region of Fig. 3 occupied by the 47 Tuc Miras. Presumably this displacement of the Miras with respect to other M type stars is due to additional sources of opacity in the 1·6-μ region. Auman (1969, especially Fig. 5) predicts a reduction in the 1·6-μ excess when the H_2O opacity is increased and Johnson *et al.* (1968) have found that H_2O bands are stronger in Mira variables than in other M giants of the same spectral type. The reason for this latter result is not yet clear. It could be due to abundance differences or to differences in atmospheric structure. In either case the 47 Tuc results show that the effect sets in rather abruptly between the semiregular, small amplitude, red giants and the large amplitude Mira stars.

Fig. 4 shows the $(J-K)_0$, $(K-L)_0$ diagram. Despite a considerable scatter, caused no doubt at least partially by the greater standard errors associated with the

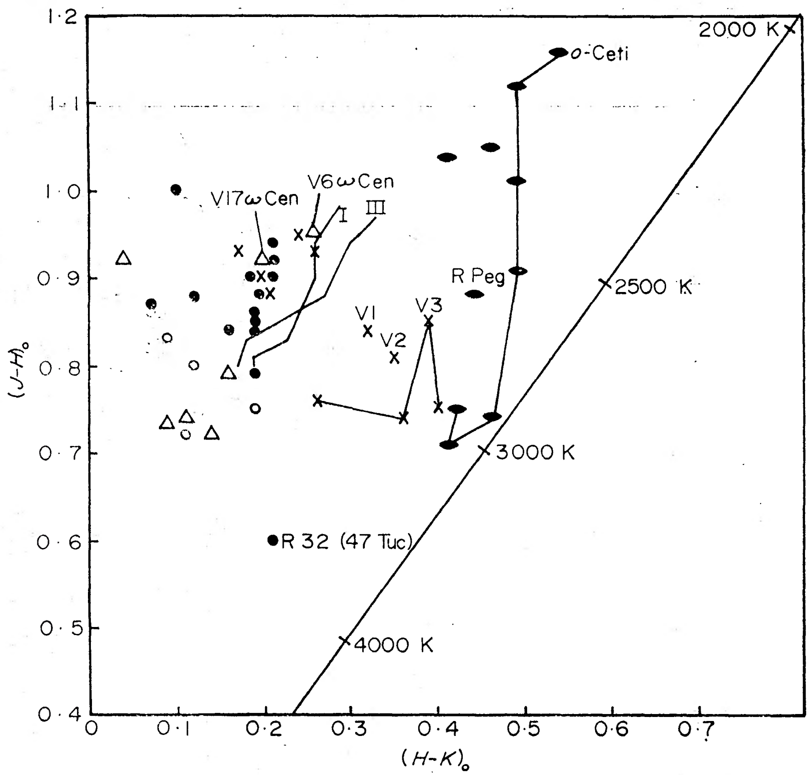

FIG. 3. $(J-H)_0$, $(H-K)_0$ *relation for ω Cen and 47 Tuc stars. The blackbody line and the mean relations for Population I luminosity class I and III stars are shown. Coding as in Fig. 2 with, in addition, field Mira variables shown by lens shaped symbols. The lens shaped symbols which are joined together are observations of o-Ceti at different epochs. Several observations of V3 47 Tuc are also joined together.*

L (3·5 μ) band measurements, the points for the 47 Tuc stars correspond in the mean to the Population I luminosity class III relation. The Mira variable V3 is displaced to the right at the phases at which these observations were made. Available data for field Miras (Mendoza 1967) are shown in Fig. 4 by lens-shaped symbols. The only field Mira with a period fairly close to that of V3 (192^d) for which photometry is available is R Vir (146^d). This star happens to fall at the position of V3. It appears from Fig. 4 that it is common for Mira variables to fall to the right of the Population I giant calibration (and also to the right of the blackbody line) in the $(J-K)_0$, $(K-L)_0$ diagram. This displacement seems to be due to an excess of radiation in the L band. In view of the discussion of the $(J-H)_0$, $(H-K)_0$ diagram

(Fig. 3) it is possible that the excess of the Miras at L is due to opacity differences compared with field M giants. However it may also be due to the short wavelength tail of low temperature radiation from a circumstellar shell. Many field Mira variables show infra-red excesses in the 10-μ region (Gehrz & Woolf 1971) indicating the existence of circumstellar shells. Such shells presumably indicate mass loss and if the second alternative is correct we thus have evidence for mass loss at the red giant tip in a globular cluster. Such mass loss has of course, frequently been postulated to occur.

Fig. 5 shows the J, $(J-K)_0$ diagram for 47 Tuc. This is given chiefly for comparison with that of ω Cen (Fig. 6). Since the range in J for the Mira variable stars is much less than in V (*cf.* Mendoza 1967, e.g. a range $\Delta J = 1^{m}\cdot 1$ for $\Delta V = 5^{m}\cdot 6$ in o-Ceti), the mean positions of the 47 Tuc Miras should not be greatly different from the plotted points. The absolute magnitude calibration assumes a true distance modulus of 13·4 (Eggen 1972).

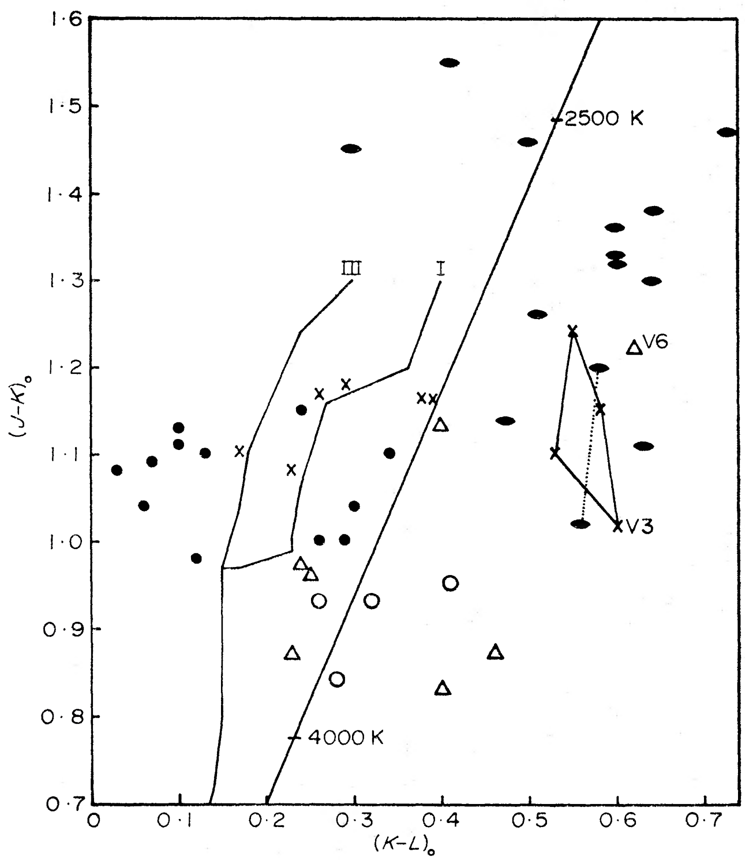

FIG. 4. $(J-K)_0$, $(K-L)_0$ *relation for* ω *Cen and* 47 *Tuc stars. The blackbody line and the mean relation for Population I luminosity class I and III stars are shown. Coding as in Fig.* 2 *with, in addition, observations of field Miras shown by lens-shaped symbols. Two observations of R Vir are joined by a dotted line and four observations of V*3 47 *Tuc are joined together.*

4. DISCUSSION OF THE ω CEN RESULTS

(a) *The non-TiO stars*

Results for ω Cen are also included in Figs 1–4 and Fig. 6. Leaving aside for the moment the M type variables V17 and V6, the diagrams show the following features for non-variable stars and giant tip (non-TiO) variables.

(1) In the $(R\text{–}I)_0$, $(J\text{–}K)_0$ diagram (Fig. 2 with $(R\text{–}I)$ values from Eggen 1972) there is good agreement with the Population I calibration which itself lies close to the blackbody line.

(2) In the $(J\text{–}H)_0$, $(H\text{–}K)_0$ diagram (Fig. 3) the ω Cen stars are displaced well above the blackbody line, showing that the continuum maximum in the H (1·65 μ) band is present in these metal-poor stars as it is in field Population I and 47 Tuc giants (*cf.* Section 3). Unfortunately detailed comparison with Population I stars cannot at present be made since few measures of field K giants in the H band have been published and so the Population I calibration cannot be extended beyond the hot end of Lee's M star calibration.

(3) In the $(J\text{–}K)_0$, $(K\text{–}L)_0$ diagram (Fig. 4) the ω Cen stars are displaced

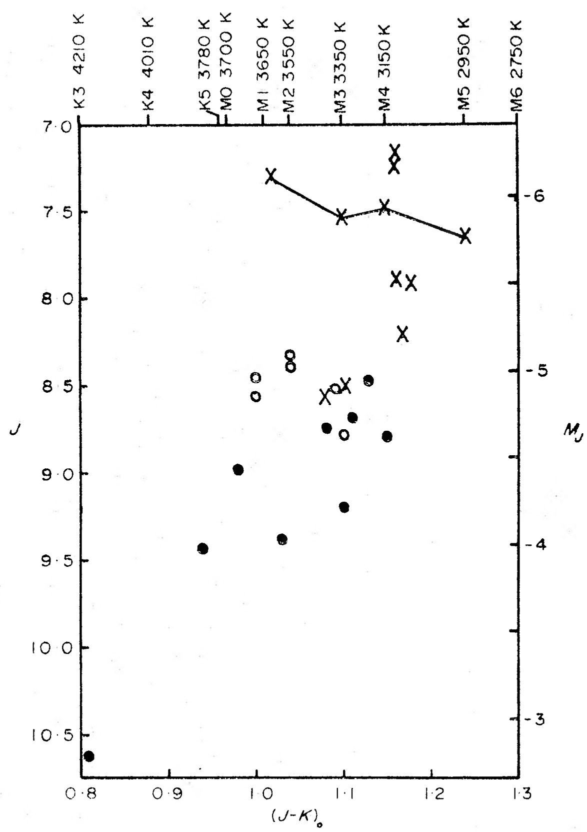

FIG. 5. *J, $(J\text{–}K)_0$ diagrams for 47 Tuc. Crosses, numbered Variables (' V ' system) from Table I(a); open circles, other small amplitude variables; filled circles, other red giants. The absolute magnitude and temperature/spectral type calibration is shown. Four observations of V3 are joined together.*

away from the Population I calibration and cluster round the blackbody line. This interesting behaviour needs confirmation from more observations and a more secure calibration of the L magnitude system for ω Cen.

(b) *Colours and spectral types of M type variables*

It has recently been found (Dickens *et al.* 1972; Feast 1973) that the small amplitude ω Cen variables V17, V6, RGO 320 and the larger amplitude variable V42 (Feast 1965) are (radial velocity) cluster members and have strong TiO bands and large $V\text{–}I_K$ colours. This was interpreted as evidence for an extension of the giant branch in ω Cen to much lower temperatures than previously associated with

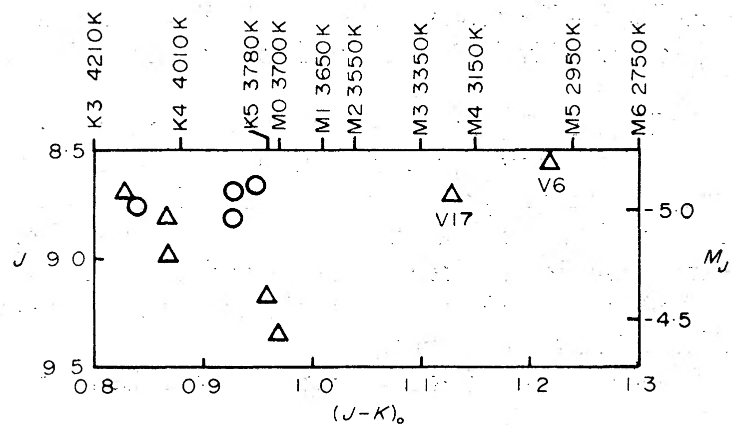

FIG. 6. *J, $(J-K)_0$ diagram for ω Cen. Triangles are 'V' numbered stars from Table I(b). Open circles are other stars. The absolute magnitude and temperature spectral type relation is shown. The M type variables V17 and V6 are marked.*

the red giant tips of metal-poor globular clusters. Since the $(V-I_K)$ colours are to a considerable extent affected by TiO blanketing it seemed desirable to obtain from J, H, K, L, photometry confirmation of the low surface temperatures of these variables and to examine them for possible abnormalities. For this reason V6 and V17 were included in our programme. Spectral types and $V-I_K$ photometry for these stars (*cf.* Dickens *et al.* 1972, and Table II) including types near the epoch of the infra-red observations indicate little change in type with time and that V17 lay in the range M3 to M4 and V6 had a type of M4 at the epoch of the infra-red observations. Fig. 6 (the J, $(J-K)_0$ diagram) shows on the upper abscissa, the calibration of $(J-K)_0$ in terms of spectral type and temperature for field Population I stars (Lee 1970; Johnson 1966). It is evident from the above that the spectral types of V17 and V6 agree well with their $(J-K)_0$ values. In the $(J-H)_0$, $(H-K)_0$ diagram (Fig. 3) V17 and V6 lie close to the (non-Mira) stars in 47 Tuc and to the calibration curve for Population I stars. Fig. 2 shows the $(R-I)_0$, $(J-K)_0$ plot. V17 lies near the Population I M giant calibration curve.*

Thus the colour-colour (infra-red) relationships for V17 and V6 are very similar to those of cool M giants of Population I. In particular the occurrence of the excess in the H band (Fig. 3) strongly implies that in the 1- to 2-μ region the sources of opacity are similar to those in the Population I stars. These results suggest that the various colours (J, H, K) may be taken as an indication of the temperature with some confidence (i.e. we can use the Population I colour–temperature calibration) as in Fig. 6.

(c) (U–B) *excesses in M type variables*

The infra-red colour–colour and colour–spectral type relations for V17 and V6 do not show any differences from Population I stars. However there is evidence that the ω Cen M type variables are differentiated from Population I stars by their $(U-B)$ colours. Fig. 7 shows a normal two-colour $(U-B)_0$, $(B-V)_0$ plot. The U,

* Eggen (1972) has also given R, I photometry for V6. However this is very discrepant with; (a) the spectral type; (b) the $V-I_K$ colour observed within 3 days of the R, I photometry (Dickens *et al.* 1972); (3) the J, H, K, L colours; (4) the energy distribution derived from U, B, V, J, H, K, L. We omit discussion of the R, I photometry of V6 pending further work.

B, *V* data is mainly from Eggen (1972). A ratio $E_{U-B}/E_{B-V} = 1{\cdot}0$ has been adopted as appropriate to cool stars (e.g. Fernie 1963) but use of the more usual ratio (0·72) would make no difference to our conclusions. The line shows the relationship between (*U–B*) and (*B–V*) for field Population I luminosity class III stars from Lee (1970) and for stars hotter than type M from Johnson (1966). It is of course well known that (*U–B*) and (*B–V*) in M stars are very considerably affected by TiO blanketing. A few of the redder stars in 47 Tuc are shown. W81 and W300 47 Tuc fall on the Population I giant calibration near the points expected for their spectral types (*cf.* Table II). They possibly have slight (*U–B*) deficiencies. V5 and V7 47 Tuc also have slight (*U–B*) deficiencies. We discuss the three ω Cen M type variables plotted in Fig. 7 in turn.

(1) *V17 ω Cen.* The TiO bands, $(V-I_K)$, (*R–I*) and *J*, *H*, *K* colours (Dickens *et al.* 1972; Eggen 1972, and this paper) all indicate a spectral type in the range M3–4. The available data at the epoch of the *U*, *B*, *V* observations are:

JD 2441000+	
093	$(V-I)_K$ gives equivalent type slightly later than M4
094	$(B-V) = 1{\cdot}75$ $(U-B) = 1{\cdot}49$
095	(*R–I*) gives equivalent spectral type M3–4
096	$(B-V) = 1{\cdot}64$ $(U-B) = 1{\cdot}31$
116	Narrow band TiO observation (0·7 μ) gives type as M3·2 ± 0·2 (Wing 1973)
127	Image Tube Spectrum gives TiO type M4.

Note that the photoelectric (*R–I*) observation should be more accurate than the photographic $V-I_K$. It seems that the spectral type at the time of Eggen's *U*, *B*, *V* observations was between M3 and M4 and almost certainly not significantly later than M4. As Fig. 7 shows the $(U-B)_0$ is $\sim 0^{m}{\cdot}4$ smaller than expected for a normal M4 giant and corresponds to type M5·5.

(2) *RGO 320 ω Cen.* The 1971 $(V-I_K)$ measures indicate a type lying in the range M2 to M3. The *U*, *B*, *V* observation (Cannon & Stobie 1973) was obtained on JD 2441477, intermediate between the two spectroscopic observations listed in Table II, both of which give M2. The $(U-B)_0$ value corresponds to an M5 Population I star and again indicates a (*U–B*) excess of $\sim 0^{m}{\cdot}4$ as for V17.

(3) *V6 ω Cen.* The 1971 $(V-I_K)$ observations indicate a type in the range M3–4. Spectra at that epoch gave M4 or M4–5. The *J*, *H*, *K* photometry gives an equivalent type slightly earlier than M5. At the epoch of the *U*, *B*, *V* observations we have:

JD 2440000+	
336	$B-V = 1{\cdot}67$ $U-B = 1{\cdot}24$
1093	$(V-I_K)$ gives equivalent type M3
1094	$B-V = 1{\cdot}52$ $U-B = 0{\cdot}91$
1096	$B-V = 1{\cdot}53$ $U-B = 0{\cdot}81$
1127	Image Tube Spectrum gives M4.

As Fig. 7 shows the (*U–B*) is that expected for a Population I M giant of type M6 or cooler. The two later observations indicate a (*U–B*) excess of $> 0^{m}{\cdot}9$. However V6 shows hydrogen emission lines (which have not been observed in V17

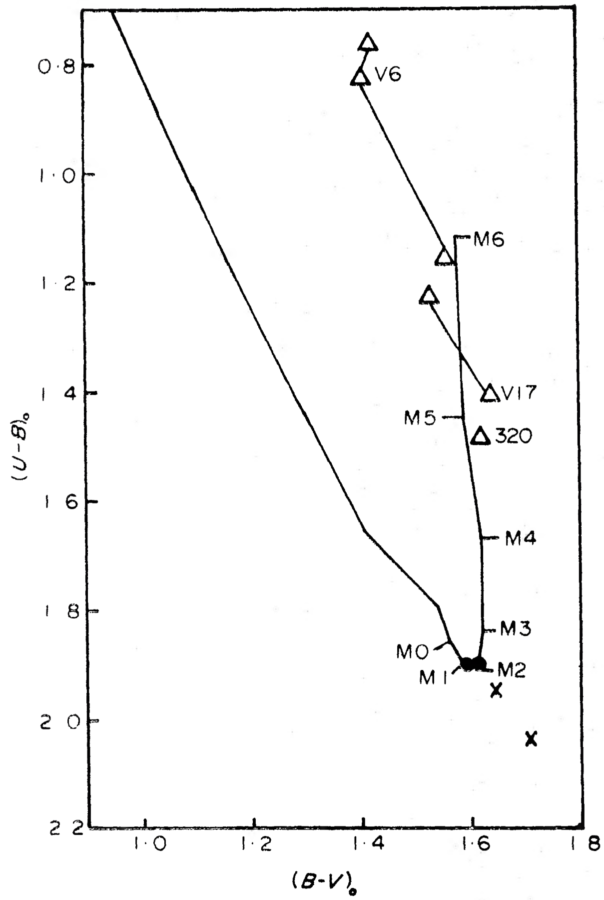

FIG. 7. $(U-B)_0$, $(B-V)_0$ *relation for some red stars in* 47 *Tuc and* ω *Cen. The* ω *Cen stars (open triangles) are named on the figure. Filled circles are W*81 *and W*300 47 *Tuc. Crosses are V*5 *and V*7 47 *Tuc. The calibration for Population I luminosity class III stars is shown. For the M types the Population I spectral types are marked on the calibration curve.*

or RGO 320) and much of the excess may be due to emission. Field Mira variables show a (*U–B*) excess which is correlated with the strength of the emission lines (Smak 1964).

Essentially the same conclusion on (*U–B*) excesses can be derived from Fig. 8 which shows Smak's (1964) results for M stars in the general field. (*U–B*) is plotted against his TiO intensity parameter *i*(TiO). Since Smak plotted observed (*U–B*) uncorrected for reddening (most of his stars are sufficiently far from the galactic plane that reddening will be small), we omit reddening corrections for the 47 Tuc and ω Cen stars. *i*(TiO) values for the globular cluster stars were determined from Smak's mean relation between *i*(TiO) and spectral type (his Fig. 15). We are here concerned with the distribution of points for *i*(TiO) less than about 0·30 or 0·40. The 47 Tuc stars fall below Smak's mean relation but relatively near other points in the diagram. The two observations of V17 ω Cen and the one of RGO 320 ω Cen fall above the mean relation (we omit V6 for reasons given above). The only two field stars which Smak finds to enter this region of the diagram are S Aql and KN Aql. Both these stars have high radial velocities (−115 and −145 km s^{-1} respectively). They are therefore candidates for halo-type objects. However in both these cases as in the case of several other field stars in the diagram, emission lines are found (in fact S Aql is often treated as a Mira variable (*cf.* Feast 1963)).

Thus the presence of a (U–B) excess unconnected with emission is less certain for these two stars than for the ω Cen variables. It is also of interest to note that the non-variable M stars which lie above the curve and which are numbered in Fig. 8 are:

(1) HD 190658 (not plotted by Smak), radial velocity -112 km s^{-1}.
(2) HD 183439 (α Vul) $U, V, W = -16, -112, +23$ km s^{-1} (Eggen 1967).
(3) HD 98118 (75 Leo) $U, V, W = -84, -27, -76$ km s^{-1}(Eggen 1967).
(4) HD 100041, radial velocity $+87$ km s^{-1}.

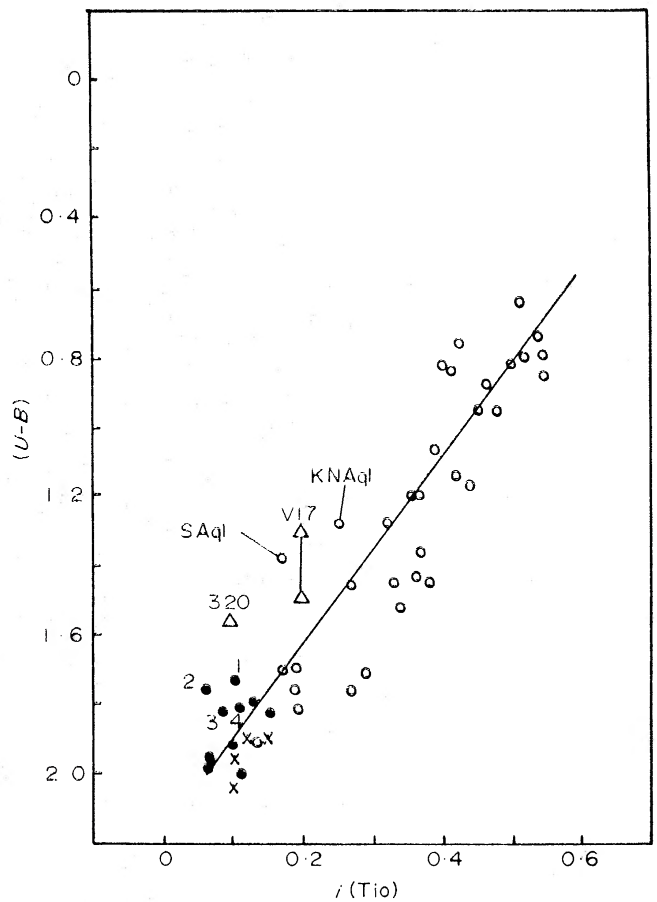

FIG. 8. *i(TiO), (U–B) relation for M type non-variables (filled circles), and variables (open circles) from the general field (after Smak). Open triangles are the M type variables V*17 *and RGO* 320 *in ω Cen. Crosses are* 47 *Tuc variables V*5, *V*7 *and W*81 *and W*300. *S Aql and KN Aql are marked. The stars numbered* 1, 2, 3, 4 *are discussed in the text.*

They are all therefore moderately high velocity objects. The stars on and below Smak's mean line are a mixture of high and low velocity stars. Eggen (1970) has also given evidence for a correlation of (U–B) excess for M stars with kinematic characteristics. It should be pointed out that the derivation of a (U–B) excess from Fig. 8 must be quite uncertain for stars near Mo since as one moves out of the M types into earlier types the (U–B) decreases rapidly (as in Fig. 7). Fortunately the ω Cen stars of interest are of type M2 or later.

We conclude that the M type variables in ω Cen show (U–B) excesses relative to field stars of the same type. These (U–B) excesses are presumably due to metal deficiency. It has generally been assumed that for giants of a given temperature the TiO band strength would be a rather sensitive indicator of metal abundance. This assumption, originally based on elementary considerations, now has the backing of some model atmosphere calculations (e.g. Goon & Auman 1970). However we have shown that the relations between the infra-red colours and the TiO band strengths for the M variables in ω Cen are similar to the relations for Population I stars. This result would come about if TiO were a major source of opacity in the region where the TiO bands are observed. This possibility has not been considered in the model atmosphere calculations but the calculations of Tsuji (1971) suggest that it is a plausible hypothesis. An abnormal abundance ratio (e.g. a high oxygen/metals ratio) could lead to an increased TiO abundance in a metal-poor star but the similarities in the relations between the infra-red colours and the TiO band strengths to those for Population I stars would then be fortuitous.

(d) *Evolutionary status of M type variables*

The red giant tip of ω Cen (as normally defined without the M type variables) has $T_{\text{eff}} \sim 3900$ K ($\log T_{\text{eff}} = 3 \cdot 59$) according to Eggen's (1972) R, I photometry and is slightly cooler according to the $(J-K)$ results (Fig. 6) ($T_{\text{eff}} \sim 3800$ K $\log T_{\text{eff}} = 3 \cdot 58$ using Johnson's (1966) calibration). These results together with a luminosity at the red giant tip of $\log L/L_{\odot} = 3 \cdot 23$ (adopting a distance modulus of 13·7 (Eggen 1972)) are in good agreement with the position of the top of the first giant branch tip (onset of the helium flash) calculated for $Z = 10^{-3}$ (Rood 1972; Demarque & Mengel 1973). The value of T_{eff} is inconsistent with calculations with $Z = 10^{-4}$ or 10^{-2} ($\sim$solar). A value of Z near 10^{-3} is consistent with a determination of Fe/H $\sim$ 1/16 solar for the bright ω Cen member HD 116745 (Fehrenbach's star) by Dickens & Powell (1973). As Fig. 6 and the earlier discussion

TABLE IV

Bolometric corrections

	B.C.	Δ
47 Tuc		
W76	−1·03	+0·06
W77	−1·02	−0·03
W78	−1·00	+0·11
W81	−1·64	+0·08
W300	−1·67	+0·12
V5	−1·54	+0·02
V7	−2·15	−0·06
ω Cen		
RGO 40	−0·72	−0·03
RGO 43	−1·01	−0·07
RGO 56	−1·00	+0·01
RGO 66	−0·93	−0·02
V53	−0·86	−0·14
V162	−0·80	−0·16
V164	−1·00	−0·17
V17	−2·51	−0·14

show the M type variables lie well beyond the conventional red giant tip and extend the giant branch to at least $T_{\text{eff}} \sim 3200$ K ($\log T_{\text{eff}} = 3{\cdot}50$) and possibly to $T_{\text{eff}} \sim 3000$ K ($\log T_{\text{eff}} = 3{\cdot}48$). These cool variables are about the same luminosity as the stars at the conventional red giant tip (the results of Table IV give $\log L/L_{\odot} = 3{\cdot}16$ for variable 17). Calculations for the second (asymptotic) red giant branch are much less certain than for the first. However it seems unlikely that the second branch can be cooler at a given luminosity than the first since this would presumably involve crossing the Hayashi line. Details of evolution beyond the second giant tip are quite uncertain. However theoretical work (e.g. Paczynski 1970; Smith & Rose 1972; Sparks & Kutter 1972) suggests that stars evolving beyond this point eject a shell and pass rapidly to the left in the HR diagram. It appears a promising hypothesis to suppose that the M type stars in ω Cen represent an early stage in evolution off the second giant branch tip and are in the process of ejecting a shell.

In the $(J-K)_0$, $(K-L)_0$ plot (Fig. 4) the M type variable with hydrogen emission lines (V6 ω Cen) appears displaced to the right into the region occupied by V3 47 Tuc (*cf.* Section 3). It seems possible that this displacement is due to excess radiation at L due to the short wavelength tail of radiation from a cool circumstellar shell. However more measurements are necessary to confirm this.

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