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S stars in ω Centauri

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Summary. The ZrO band at 6473 Å has been found in 10 of the 12 stars previously found to have TiO bands, indicating that these are MS or early S stars. The stars also show strong metal lines and in particular strong Ba II λ4554, in common with hotter fainter stars which are also found to lie to the red (cool) side of the giant branch of ω Cen in the *I*, *V–I* diagram. These stars are much fainter than MS stars in the Magellanic Clouds and are not associated with carbon stars as the latter are. It is likely that they represent the top of the range of metal abundance in ω Cen and that the strong Ba II and ZrO features result from a primordial excess of s-process elements.

1 Introduction

ω Centauri is unique among metal-poor globular clusters in possessing a giant branch extending to spectral type as late as M4 (Dickens, Feast & Lloyd Evans 1972). These stars were at first interpreted as being in an unusual evolutionary state in the forbidden region to the right (cool) side of the Hayashi line. The demonstration of the exceptional width of the giant branch (Cannon & Stobie 1973) led to the suggestion that the M stars represent the red giant tip of a population having a metal content greater than that of the bulk of the stars in ω Cen (Lloyd Evans 1975) and the discovery of a range of metal abundance among the RR Lyrae stars led to the same conclusion (Freeman & Rodgers 1975). Lloyd Evans (1977a, b) found another seven stars with TiO bands, fainter than those found earlier and not detectably variable. These and other hotter stars lying close to the locus of the 47 Tuc giant branch showed similar metal line strengths to stars in 47 Tuc although the λ4554 line of Ba II was generally stronger in ω Cen (Lloyd Evans 1977b).

2 Observations

VI photometry (Lloyd Evans 1977a, b) revealed that some of these stars lie well to the red side of even the 47 Tuc locus in the *I*, *V–I* diagram, reviving the idea of stars in some rare terminal evolutionary state. Photographic image tube spectra at 60 Å mm^{-1} were taken to check for possible Hα emission in 15 stars, revealing emission or incipient emission only in the variable stars (Lloyd Evans 1983a, b). Many of these spectra showed the $\gamma(0,0)R_3$

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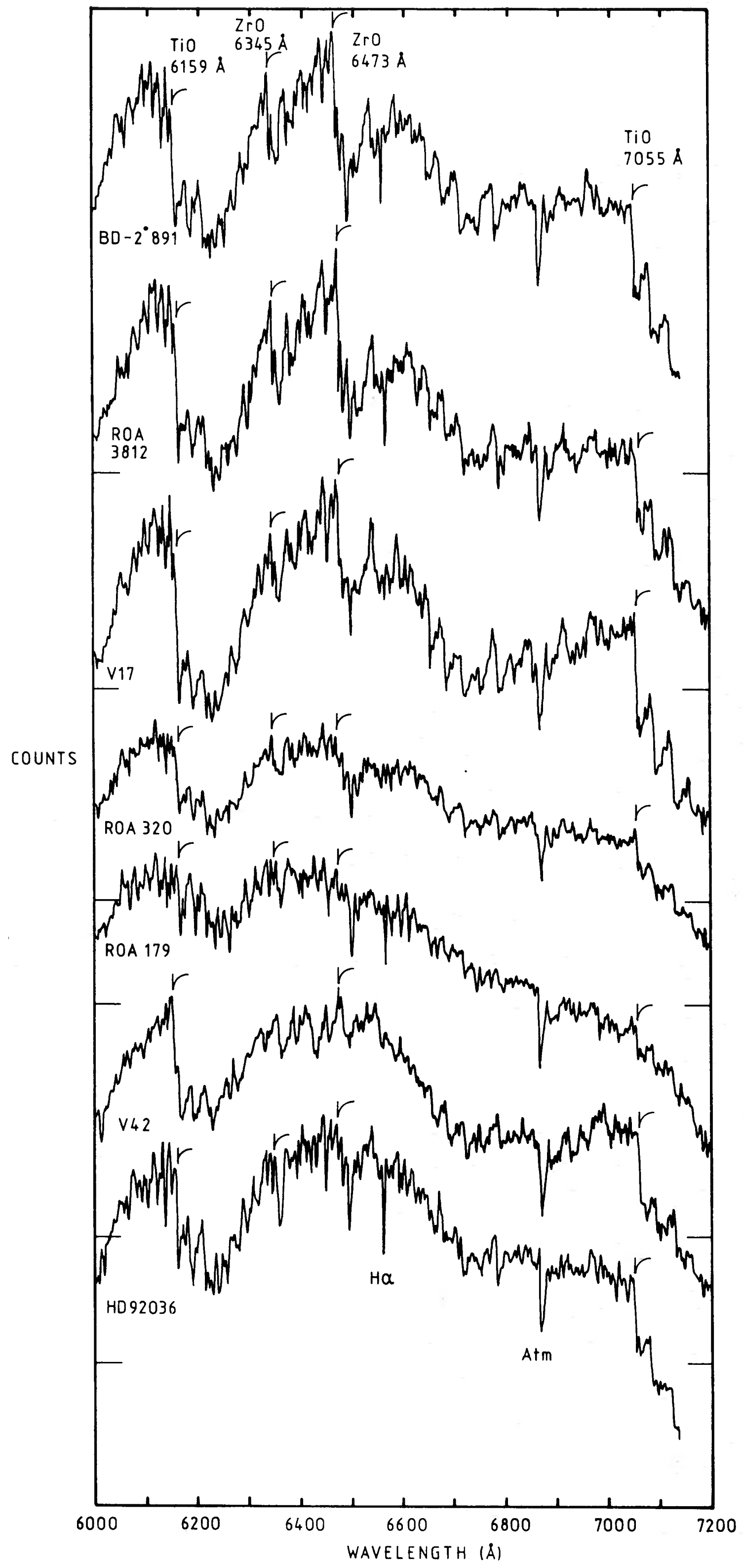

(a)

Figure 1. (a) Spectra of ω Cen stars in the wavelength range 6000–7200 Å. The RPCS spectra have been smoothed with a triangular function having FWHM of 4 Å. The stars shown are ROA 3182, V17, ROA 320, ROA 179 and V42. ROA 320 is a variable of small amplitude (Dickens, Feast & Lloyd Evans 1972). Two field stars are shown for comparison: HD 92036, M2 III and BD – 2°891, S2/2 or M2S (Keenan & Boeshaar 1980). (b) Spectra of the same stars in the wavelength range 6400–6600 Å, showing the band-heads of ZrO at 6473 Å and TiO at 6479 Å as well as Hα which is strongly in absorption in the stars of low luminosity but not in the variables. The RPCS spectra have been smoothed with a triangular function having FWHM of 3 Å.

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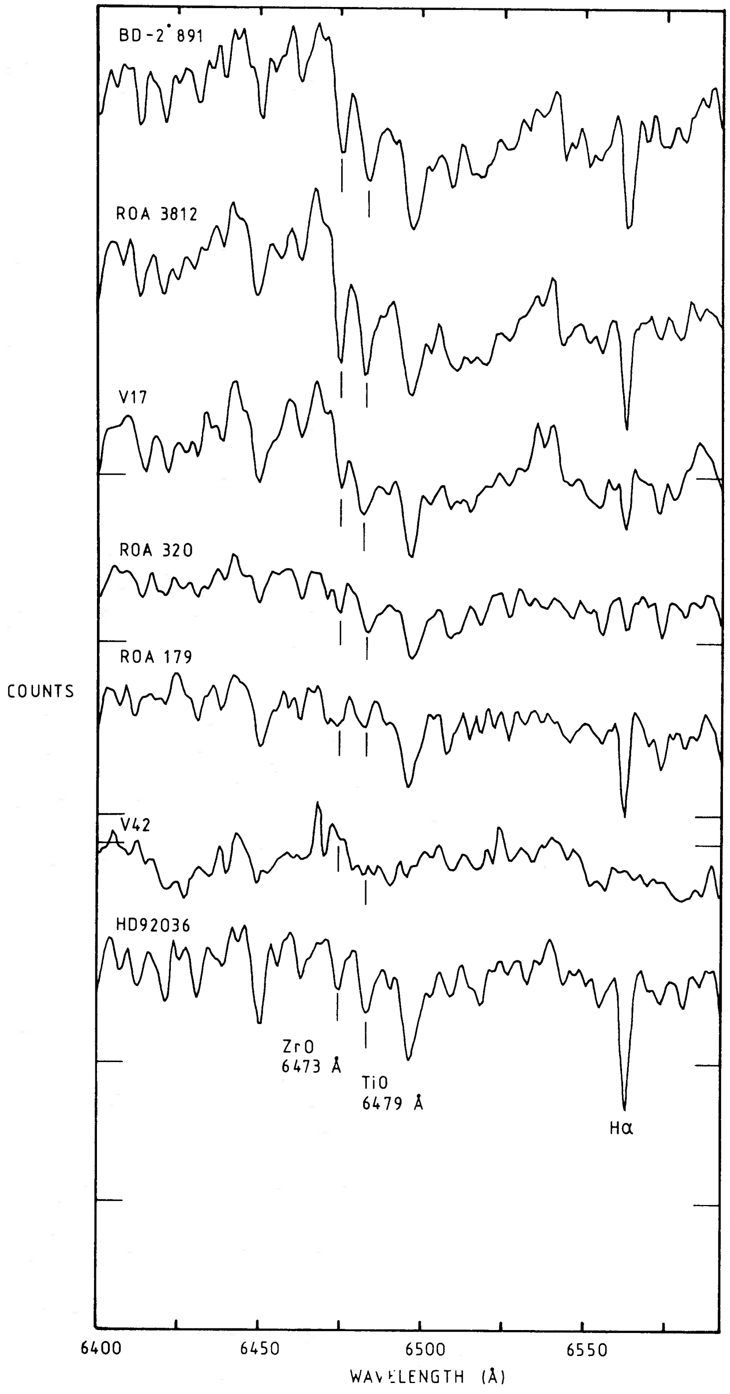

(b)

Figure 1 – *continued*

bandhead of ZrO at 6473 Å. Spectra with improved signal : noise were taken with the reticon photon counting system (RPCS: Jorden, Read & van Breda 1982; *SAAO Facilities Manual* 1982) in place of the photographic plate in 1982 April. The slit width was 300 μm, projecting to 2 arcsec, in all the observations, giving a resolution of 1.5 Å.

The TiO bandstrengths measured on the photographic spectra were combined with those obtained from spectra in the 4800–6200 Å region (Lloyd Evans 1983b, c). Examples of the new RPCS spectra are shown in Fig. 1.

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Table 1. Spectroscopic data for ω Cen stars.

Star	Vel.	ΔTiO		ΔZrO	ZrO	Ba II	Spectral
	km s^{-1}	Pg	RPCS	RPCS	Pg, RPCS	Δ log *I*	type RPCS
V6	+231	0.21–0.33	0.27	0.08	1, 1	0.23	S3/1
V17	+227	0.30	0.26	0.12	2, 3	0.28	S4/1–2
V42	+249	0.33:	0.16	0.01	0, 0	–	M2.5
ROA 179	+218	0.10	0.08	0.04	1, 0	0.22	M/S:
201	+208	0.15	0.17	0.09	1–2, 2	0.27	S2.5/1–2
300	+215	0.09	0.10	0.09	2, 2	0.25	S2/1–2
320	+233	0.13–0.20	0.12	0.07	2–, 1–2	0.27	S2/1–2
371	–	0.06	–	–	0, –	0.37	K5:
425	+225	0.13	0.14	0.17	3, 3	0.39	S3/2
447	+208	0.12	0.11	0.11	2, 2	0.39	S2/2
500	+224	0.09	0.04	0.00	1, 0	0.27	K5:
513	+203	0.12	0.14	0.17	–, 3	0.26	S3/2
517	–	0.08	–	–	0+, –	0.26	K5:
523	–	0.06	–	–	0–1, –	0.25	K5:
3812	+215	0.19	0.21	0.21	3, 3	0.30	S4/2–3
5293	+226	0.11	0.11	0.12	2, 2	0.33	S2/2

Notes

The spectral types given in the last column were uncertain because of the small number of standards, two I giants and four S stars from Keenan & Boeshaar (1980) whose classification scheme is used.

All the stars have strong absorption at Hα except for V6 (strong emission), V17 (weak absorption), V4 (no Hα), ROA 201 (weak absorption) and ROA 320 (weak absorption, appearing as the core to very wea emission).

3 Results

3.1 RADIAL VELOCITY

Radial velocities were obtained from the RPCS spectra by cross-correlation with the spectra of standard stars, using a program written by J. W. Menzies. Standards observed on earlier runs (Lloyd Evans 1983d) were used because bad weather prevented standard star observations in 1982 April: these standards are listed in Table 2. This is permissible as the zero point with the image tube spectrograph appears stable to ~ ± 10 km s^{-1}. The radial velocities (Table 1) confirm the earlier finding (Dickens *et al.* 1972; Feast 1973; Lloyd Evans 1977a, b) that these stars are members of ω Cen. The mean velocity is +222 km s^{-1}, with a standard deviation of one star about the mean of ± 12 km s^{-1}, in satisfactory agreement with the published cluster velocity of +238 km s^{-1} (Kinman 1959; Harding 1965). Comparison with the velocities measured for 11 of these stars on photographic image tube spectra gives a mean difference of zero, with standard deviation for one star of ± 18 km s^{-1}. The internal standard error of a single velocity from Table 1 is only ± 4 km s^{-1}.

3.2 BAND STRENGTHS

The TiO band strengths measured on the photographic spectra (Lloyd Evans 1983b) are given in Table 1, together with the values from the prominent 6159 and 7055 Å bandheads on the RPCS spectra. The bandheads are affected to some extent in the spectra of stars with strong ZrO: in particular the 6159 Å bandhead appears to be weaker because the region imme-

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Table 2. Data for standard stars.

Star	Spectral type	Ref.	ΔTiO	ΔZrO	ZrO class	RV km s^{-1}	Notes
(a) Observed with IPCS at SAAO.							
HD 114586	S5+/2.5	1	0.28	0.23	4		
NQ Pup	S4.5/2	1	0.35	0.20	3–4	−12	5
ST Sco	S8/4.5	1	0.24	0.58	5		
V635 Sco	S6/3+	1	0.26	0.38	5		
(b) Observed with RPCS at SAAO.							
HD 43455	M2.5–3 III	4	0.23	0.05	0	+38	6
HD 49683	M4S	2	0.35	0.13	3	+3	
HD 63733	S3.5/3	1	0.12	0.19	3	−18	7
HD 82077	M1 III	3	0.08	0.01	0	−5	8
HD 92036	M2 III	3	0.17	0.05	0+	+11	9
BD − 2° 891	S2/2:	1	0.20	0.14	2–3	−16	
NQ Pup	S4.5/2−	1	0.29	0.22	3	−12	

References and notes

1. Keenan & Boeshaar (1980)
2. Keenan (1954)
3. Buscombe (1977)
4. Buscombe (1981)
5. Uses the value found with RPCS below
6. +34.5 Campbell & Moore (1928)
7. +3.9 Keenan & Teske (1956)
8. −8 v Wilson & Joy (1950)
   −7.9 Abt (1970 Large velocity range
9. +14.8 Campbell & Moore (1928).

The velocity system adopted depends on HD 43455 and 92036 only, because HD 82077 is variable and the large residual for HD 63733 is not understood although it may result from the different band strengths.

diately to the blue of the bandhead is reduced in intensity. The 6473 Å $\gamma(0,0)R_3$ bandhead of ZrO has been measured in all stars: standard stars classed as S or MS (Keenan & Boeshaar 1980) have ΔZrO > 0.13, while normal M giants have ΔZrO ~ 0.05 (Lloyd Evans 1983d). The ΔTiO and ΔZrO values given in Tables 1 and 2 are the log intensity values of the depression of the bandhead below a hand-drawn continuum which, in the case of a sharp bandhead, coincides with the peak immediately to the blue of the bandhead. The bandhead and the depressed region extending some 80 Å to longer wavelength are considered in estimating ZrO bandstrength on a scale of 0–3, with generally good agreement between photographic and RPCS results (Table 1).

Smaller enhancements of ZrO than in any of the available standards can be discerned among the ω Cen stars: ΔZrO ~ 0.07 appears to be an approximate dividing line. Spectral types have been estimated on Keenan & Boeshaar's (1980) system, with considerable uncertainty because of the lack of suitable standards with very weak ZrO: see Table 2. Ten of the 16 stars in Table 1, including all the brighter stars except V42 and probably ROA 179, are MS stars. The four hotter stars ROA 371, 500, 517 and 523 lack prominent bands of either TiO or ZrO and in view of the RPCS data for 500 none of them can be considered as MS stars.

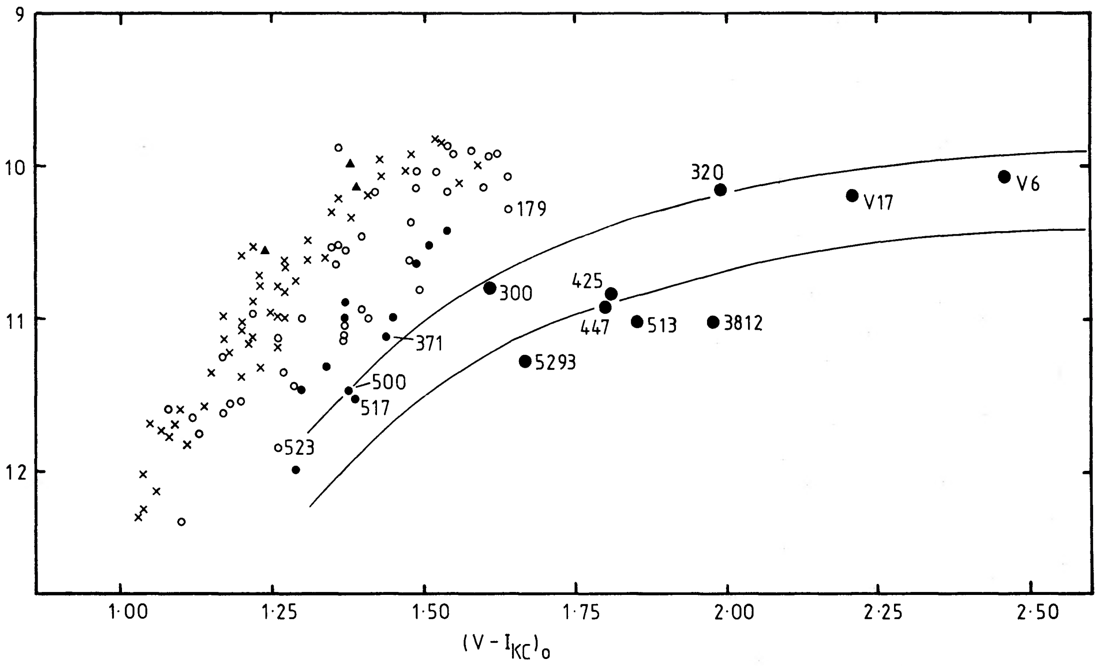

Figure 2. The I_{KC}, $(V-I_{KC})_0$ diagram for ω Cen. Crosses, stars with Ba II 4554 Å having $\Delta \log I < 0.15$; open circles, $0.15 \leqslant \Delta \log I \leqslant 0.25$; filled circles, $\Delta \log I > 0.25$. Large filled circles, MS stars. Filled triangles, CH stars. The mean locus for 47 Tuc giants is shown for two different assumptions regarding the horizontal branch luminosities of the two clusters (Section 3.5). The $E(V-I_{KC})$ values are: ω Cen, 0.14 mag; 47 Tuc, 0.05 mag. Redder stars are over-represented in this figure.

3.3 Ba II LINE STRENGTH

Dickens & Bell (1976) reported the strong Ba II 4554 Å line of ROA 371 and several additional examples were found by Lloyd Evans (1977b). Measurements of line strengths in a large sample of stars (Lloyd Evans, to be published) confirm that Ba II is strong in most of the stars which fall well to the right of the main giant branch in the I, $V-I$ diagram. The values given in Table 1 are all fairly large: most of the 220 stars observed have $\Delta \log I < 0.20$ as do most of the few stars observed in other clusters, and some of the Ba II stars observed by Catchpole, Robertson & Warren (1977) have weaker Ba II than these. The stars which are cool enough to show TiO bands suffer substantial blending at 4554 Å, but the large values found in somewhat hotter stars provide strong confirmatory evidence. The stars plotted in the I_{KC}, $(V-I_{KC})$ diagram (Fig. 2) are coded for their Ba II strengths, showing that strong Ba II is a feature of stars well to the red of the main giant branch.

3.4 CH AND CN

The 4216 Å CN bands weaken rapidly with declining temperature in late K and early M stars so that the measurements are not meaningful, but the hotter stars with strong metallic lines and strong Ba II have strong CN while the G band of CH is weaker than in Ba II stars (Lloyd Evans, in preparation). These stars are not similar to field Ba II stars and are also distinct from the strong CN stars in ω Cen which Bessell & Norris (1976) and Glass & Feast (1977) find to have an energy distribution akin to those of Ba II and CH stars in the field. The latter group in ω Cen do not usually have outstandingly strong Ba II nor do they stand far to the red of the main giant branch in the I, $V-I$ diagram, our primary selection criterion. Some of them are probably less extreme cases of the strong metal, strong Ba II group, however.

3.5 COLOUR–MAGNITUDE DIAGRAM

Fig. 2 shows the I_{KC}, $(V-I_{\mathrm{KC}})_0$ diagram based on photoelectric photometry (Lloyd Evans 1983e). A mean giant branch for 47 Tuc is also shown, with two different assumptions regarding the relative distance moduli: (a) 0.46 mag, assuming equal absolute magnitude on the horizontal branch (Harris 1976); (b) 0.96 mag, assuming the maximum likely difference in horizontal branch absolute magnitude of 0.5 mag (Sandage 1982). The cool envelope of the most metal-rich stars in ω Cen has a similarity to the 47 Tuc giant branch, with a few stars to the red of the latter even with the second assumption.

3.6 TWO-COLOUR DIAGRAM

The $(U-B)_0$, $(V-I_{\mathrm{KC}})_0$ and $(B-V)_0$, $(V-I_{\mathrm{KC}})_0$ diagrams are plotted in Figs 3(a) and (b) using data from Eggen (1972a), Cannon & Stobie (1973) and Lloyd Evans (1983e). The fiducial line for field giants is based on the data of Menzies, Banfield & Laing (1980). The ultraviolet excesses of the variables V6 and ROA 320 are plausibly correlated with their H emission (Glass & Feast 1973). The remaining MS stars and the hotter star ROA 371 which has strong Ba II fall close to the fiducial line for normal giants. This contrasts with the unusually red $B-V$ of MS stars in the field (Smak 1968; Eggen 1972b) and in the Magellanic Clouds (Lloyd Evans 1983d).

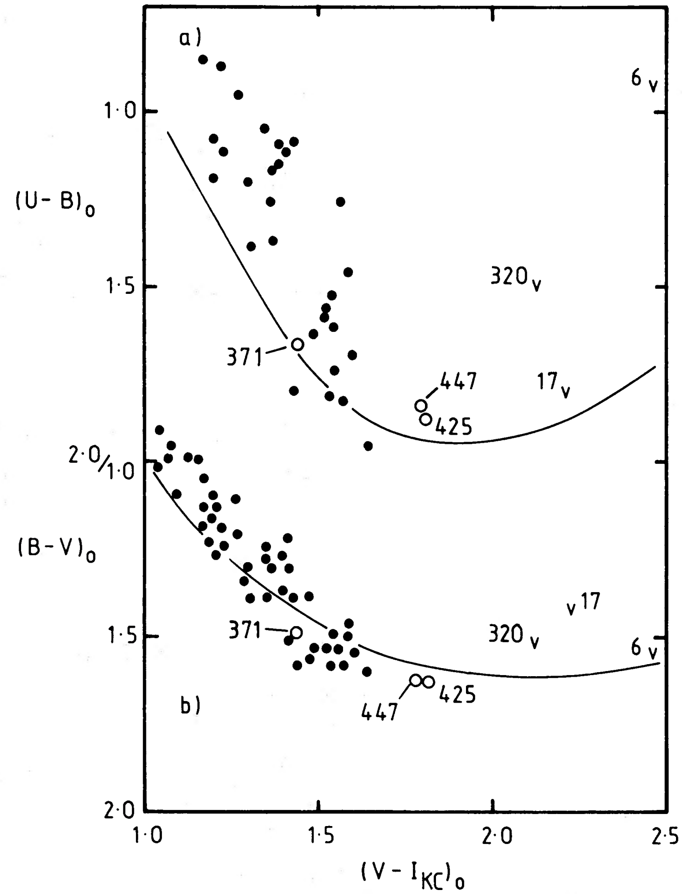

Figure 3. (a) The $(U-B)_0/(V-I_{\mathrm{KC}})_0$ diagrams for ω Cen. The MS stars and the strong Ba II star ROA 371 are represented by open circles. The fiducial line is from the data of Menzies, Banfield & Laing (1980). (b) the $(B-V)_0/(V-I_{\mathrm{KC}})_0$ diagram for ω Cen.

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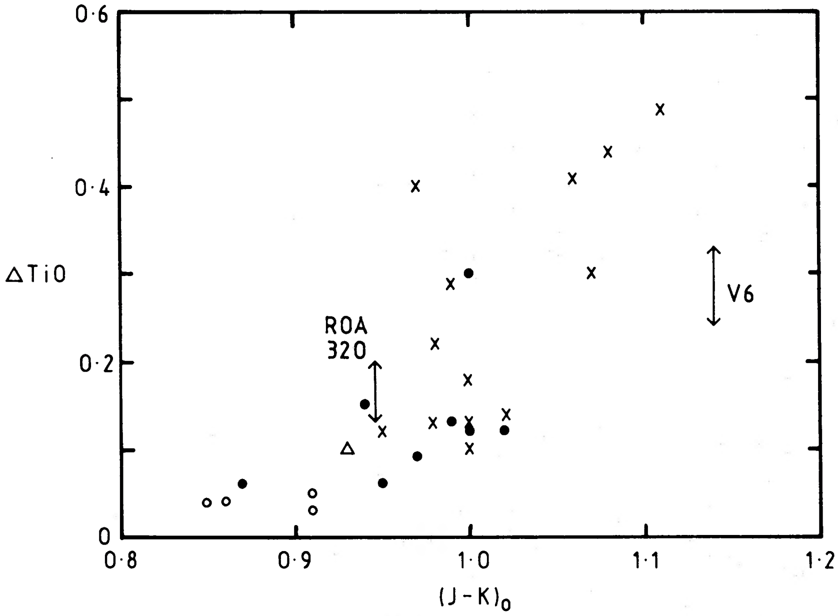

Figure 4. The titanium oxide band strengths ΔTiO determined from photographic measures (Lloyd Evans 1983b), are plotted against $(J-K)_0$ colours from Frogel *et al.* (1981) for 47 Tuc and Persson *et al.* (1980) for ω Cen. Crosses: 47 Tuc stars; open circles: weak-lined stars in ω Cen; open triangle: ROA 179; filled circles: MS stars and stars with strong Ba II. The ranges of variation of ΔTiO encountered in V6 and ROA 320 are shown; the true ranges may be greater and a range of colour is possible.

3.7 ABUNDANCES FROM TiO BAND STRENGTHS

Mould & McElroy (1978) and Mould, Stutman & McElroy (1979) estimated the metal content of globular clusters from plots of TiO band strength against a near-infrared colour index which is itself not greatly affected by the bands. The TiO band strengths (Lloyd Evans 1983b) of stars in 47 Tuc and ω Cen are plotted against the $(J-K)_0$ colours determined by Frogel, Persson & Cohen (1981) and Persson *et al.* (1980) (Fig. 4). The TiO stars in ω Cen are intermingled with the 47 Tuc stars, suggesting similar metal abundance. Some of the scatter probably results from variability; V6 is the only one of the TiO stars (V42 is not included) which might have lower metal abundance on the basis of this criterion. The TiO band strengths measured for the MS stars of ω Cen may be underestimated, however, in view of the presence of strong ZrO bands which are not seen in the 47 Tuc stars (Lloyd Evans 1983d).

4 Discussion

Observations of Magellanic Cloud clusters of intermediate age suggest that MS stars represent an evolutionary stage between M and carbon stars, where substantial enrichment of the stellar atmosphere with carbon and heavy elements has occurred although the C/O ratio is still less than unity (Bessell, Wood & Lloyd Evans 1983; Lloyd Evans 1983d). Their luminosity, $M_{\rm bol} \sim -4.3$, is less than the theoretical minimum for this type of surface enrichment (Iben 1981) but greater than the maximum luminosity attained in galactic globular clusters. The absence of very red stars in the oldest Magellanic Cloud clusters (Lloyd Evans 1980) results from the lower luminosity reached by giants in these clusters (Aaronson & Mould 1982), and for the same reason MS stars and cool carbon stars are not expected in galactic globular clusters.

The MS stars in ω Cen cover a substantial range in bolometric magnitude, the faintest having $M_{\rm bol} \sim -2.4$ (Persson *et al.* 1980), some 2 mag fainter even than those in the Magellanic Cloud clusters. There are several other differences between the two sets of MS stars. They do not bear the same relationship to carbon stars: the carbon stars in the Magellanic Cloud clusters are brighter and cooler than the MS stars (Bessell *et al.* 1983) but no cool carbon stars are known in ω Cen. The CH stars are much bluer and lie on or near the main (metal-poor) giant branch (Fig. 2) and are probably not at the same evolutionary stage as the cool carbon stars of the Magellanic Clouds. This distinction between two types of carbon stars has been made in dwarf spheroidal galaxies (Frogel *et al.* 1982).

The absence of the deficiency of violet and ultraviolet light which occurs in other MS stars (Section 3.6) suggests that the ω Cen stars may not share the increased C/O ratio which is a probable characteristic of the others. The association of the MS stars with the strong lined, Ba II enhanced stars which lack the stronger G band found in field Ba II stars as well as in the CH stars in ω Cen (Section 3.4) also suggests a relatively normal C/O ratio.

These considerations point to a different origin for the enrichment of s-process elements in the ω Cen stars. Their location in the *I*, *V–I* diagrams (Lloyd Evans 1977a, b; Fig. 2) and in the infrared colour–magnitude diagram (Persson *et al.* 1980), the strong lines (Lloyd Evans 1977b) and the strong TiO bands (Section 3.7) all suggest that they represent the high metal content tail of the abundance range in ω Cen. The calibrations of Figs 2 and 4 suggest a metal abundance similar to that of 47 Tuc, and some of the RR Lyrae stars also fall in this range (Freeman & Rodgers 1975; Butler, Dickens & Epps 1978). The high dispersion abundance determinations (Cohen 1981; Mallia & Pagel 1981) do not extend to the extreme cases and must underestimate the upper limit to metal abundance in ω Cen. The metal-rich population of ω Cen differs from 47 Tuc stars in having stronger CN and Ba II (Lloyd Evans 1977b), different DDO colours (Norris 1978), a horizontal branch extending at least as far as the RR Lyrae instability strip (Freeman & Rodgers 1975) and a type II Cepheid, V29, which has strong CN and Ba II (Lloyd Evans 1978).

Norris and Lloyd Evans both suggested the possibility of a high primordial abundance of barium in the metal-rich ω Cen stars (discussion following paper of Lloyd Evans 1978). Sneden, Lambert & Pilachowski (1981) have made a similar suggestion for the mild Ba stars in the field, which lack the enhanced carbon abundance of the classical Ba II stars. The MS stars in ω Cen may be the first stars found in which unusual molecular band strengths result from an initial distribution of the heavy elements which differs from the norm rather than being the result of nuclear processing within the stars themselves. A point in favour of this interpretation is that the degree of enhancement of ZrO, given by the second number of the spectral type in the Keenan–Boeshaar system (Table 1), is greater on average the fainter a star lies with respect to the 47 Tuc locus in Fig. 2. This indicates that the molecular bands follow the same trend of [s/Fe] increasing with [Fe/H] indicated by the behaviour of the Ba II line in hotter stars, given that location relative to the 47 Tuc locus in Fig. 2 is a measure of Z and hence of [Fe/H].

Acknowledgments

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