THE ROLE OF MIXING AND PRIMORDIAL ABUNDANCE VARIATIONS IN 47 TUCANAE AND ω CENTAURI

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1. INTRODUCTION

It has become clear in recent years that widespread and complex abundance variations exist among the stars of several globular clusters. ω Cen is the prime example, containing CH stars, weak-G-band stars, CN strong stars, TiO stars, and (not least) RR Lyrae stars possessing an anomalous range in calcium line strengths. (Harding 1962; Freeman and Rodgers 1975; Norris and Bessell 1975, 1977; Dickens and Bell 1976; Bessell and Norris 1976; Lloyd Evans 1977) The extent to which these phenomena result from primordial abundance variations or from the mixing to the surface of material processed by nuclear reactions is currently the subject of some debate. The present paper presents a short account of investigations of the giant and horizontal branches of 47 Tuc and of several giants in ω Cen. The results were obtained in collaboration with M. S. Bessell and K. C. Freeman, and will be fully reported in papers being prepared for submission to Astrophysical Journal. Most emphasis will be placed on 47 Tuc, where we have sought to address four problems. (i) How widespread are the CN anomalies reported by McClure and Osborn (1974), Bell, Dickens, and Gustafsson (1975), and Hesser, Hartwick, and McClure (1977) - both throughout the HR diagram and in relative frequency? (ii) Is there any correlation between the relative frequency of the CN anomaly with radial position in the cluster, which might correlate with the color gradients observed by Gascoigne and Burr (1956) and Chun (1976)? (iii) Is there any evidence for G-band variations similar to those found generally in the metal poor ([Fe/H]< -1) globular clusters? (cf. Zinn 1973, 1977; Mallia 1975; Norris and Zinn 1977) (iv) Are the CN variations accompanied by variations in the abundance of the heavy elements?

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Finally we address the question of the relationship between the TiO stars in 47 Tuc and ω Cen.

2. 47 TUCANAE

Our investigation of 47 Tuc is based principally on 50Å mm^{-1} spectra obtained with the 1.9 m telescope at Mount Stromlo, together with several 33Å mm^{-1} spectra obtained with the 4 m telescope at Siding Spring Mountain. Two series of spectra were obtained at Mount Stromlo. The first consists of stars in the outer regions of the cluster ($r > 10$ arc min), and comprises 16 red giant branch, 12 asymptotic giant branch, and 14 horizontal-branch stars. The second comprises 16 red giant and 2 asymptotic giant branch stars in the inner regions (60 arc sec $< r <$ 120 arc sec). These observations were supplemented by UBV and DDO intermediate band photometry obtained with the 1 m telescope on Siding Spring Mountain, together with the data of McClure and Osborn (1974), Cannon (1974), Lee (1977), and Hesser _et al_. (1977).

In Fig. 1 we show the blue spectral region in selected pairs of stars of similar magnitude and color on the red giant branch, the asymptotic giant branch, and the horizontal branch. Inspection

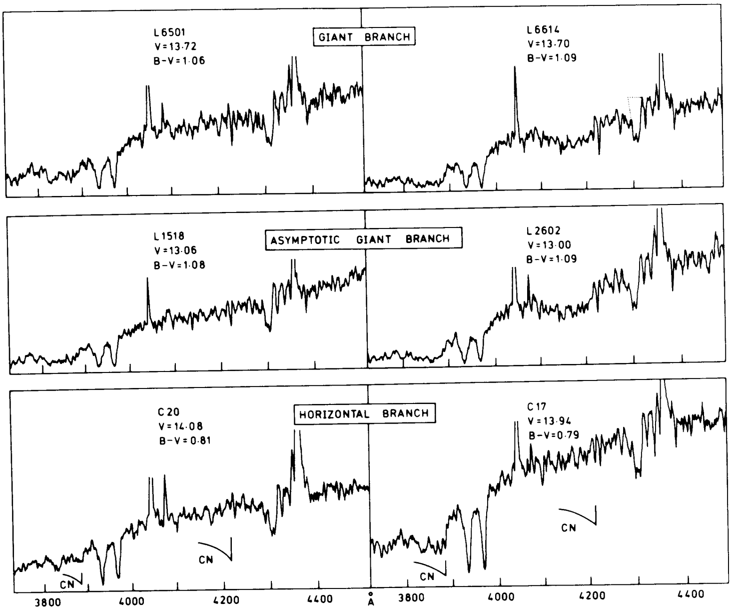

Fig. 1. Spectra of pairs of stars of similar magnitude and color on the red giant, the asymptotic giant, and horizontal branches. The CN strong stars are shown on the right. (Nomenclature from Lee [1977] and Cannon [1974]).

of the CN bands at 4216 and 3883 Å shows that the CN anomaly is widespread throughout the HR diagram, occurring on all three branches.

2.1 The Red Giant And Asymptotic Giant Branches

On each spectrum of the red giant and asymptotic giant branch stars we have computed a CN index defined by $S(4142) = -2.5 \log [\int_{4120}^{4216} F_\lambda d\lambda / \int_{4216}^{4290} F_\lambda d\lambda]$. The existence of DDO photometry for 12 stars in our sample allowed us to compare S(4142) with the corresponding DDO index C(4142). A close correlation exists and was used to transform the C(4142) values for a further 15 stars, for which this index is available, onto the S(4142) scale. This body of data is shown in the [S(4142),(B-V)]- plane in Fig. 2. Adopting the lower envelope of the data as the lower limit to the CN index, the CN anomaly δS(4142) was measured for each star as the distance the star lay above the lower envelope at its observed (B-V). (For completeness it should be noted that the asymptotic giant branch stars appear to be systematically CN stronger by 0.05 mag than the red giants. To allow for this effect a lower envelope displaced upwards by this amount was adopted for this group.)

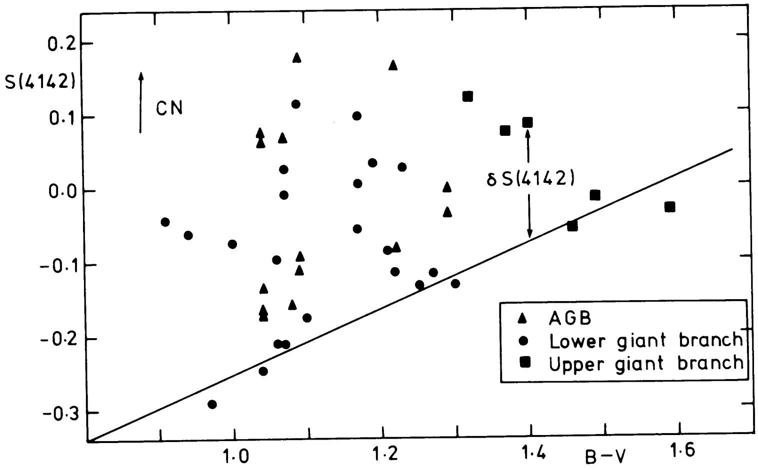

Fig. 2. 47 Tuc giants in the S(4142), (B-V) - plane. The direction of increasing CN is shown.

The histograms of δS(4142) represent the principal results of our investigation and are shown in Fig. 3 for the outer and inner regions of 47 Tuc. Two conclusions may be derived from these data. First, in the outer regions there appear to be two populations in approximately equal numbers. In this region this conclusion is approximately true for the red giant branch stars and for the

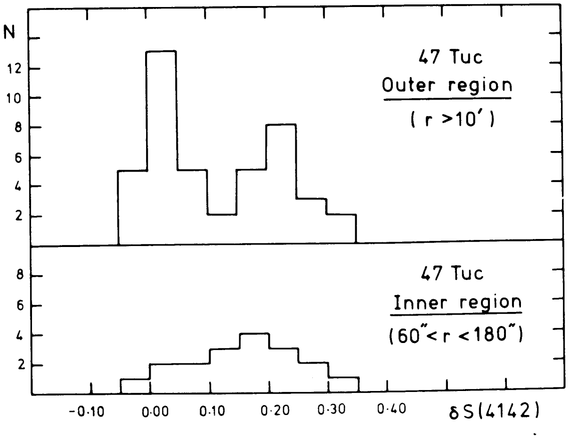

Fig. 3. Histogram of δS(4142) for stars in the inner and outer regions of 47 Tuc.

asymptotic giant branch stars, and as we shall see in what follows the same pertains to the horizontal-branch sample. These results are extremely difficult to understand in terms of mixing at the helium core flash (or the helium shell flashes). Any scenario involving partial mixing at the core flash, of the type investigated by Rood (1970), would most likely result in different proportions of mixed objects on the horizontal and giant branches. If mixing is to be invoked, one appears forced to postulate that it occurs below the luminosity considered in the present sample. This corresponds to just below the level of the horizontal branch.

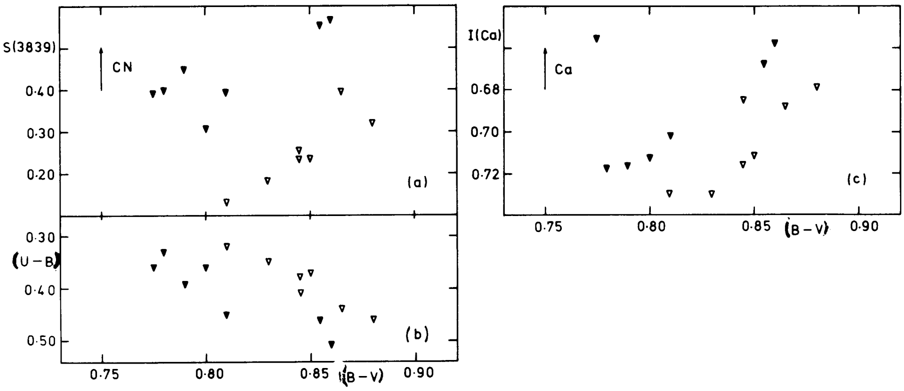

Fig. 4. Horizontal-branch stars in the (a) [S(3839), (B-V)] - plane, (b) [(U-B),(B-V)]- plane, and (c) [I(Ca),(B-V)]- plane. Filled and open symbols refer to strong and weak CN stars as defined in Fig.4a.

The second conclusion one may derive from Fig. 3 is that in contrast to the outer region, the inner region is CN strong. It seems reasonable to conclude that this effect is closely related to the color gradients observed in this cluster. (cf. Chun 1976)

2.2 The Horizontal Branch

As demonstrated in Fig. 1, CN anomalies exist also on the horizontal branch. From our spectra we have measured the CN index $S(3839) = -2.5 \log \left[\int_{3846}^{3883} F_\lambda d\lambda / \int_{3883}^{3916} F_\lambda d\lambda \right]$, and show our results in the [S(3839),(B-V)]- plane in Fig. 4a. (We note that the CN band at λ4216 has greatly weakened at the higher temperature of the horizontal branch). Here too there appear to be two classes of CN strengths. In Fig. 4b we show our sample in the [(U-B), (B-V)]- plane where the open and filled symbols represent weak and strong CN stars as defined in Fig. 4a. It is clear that the CN strong stars have the smaller ultraviolet excesses. Finally in Fig. 4c we plot a measure of the CaII H and K line strengths defined by $I(Ca) = \int_{3916}^{3985} F_\lambda d\lambda / \left[\int_{3883}^{3916} F_\lambda d\lambda + \int_{3985}^{4016} F_\lambda d\lambda \right]$. Here we see an apparent correlation of Ca with CN, in the sense that at a given (B-V) the CaII lines are stronger in the CN strong stars.

2.3 G-Band And MgI Measurements

Our G-band (CH molecule) measurements for all stars in the outer region are shown in the [W(G),(B-V)]- plane in Fig. 5,

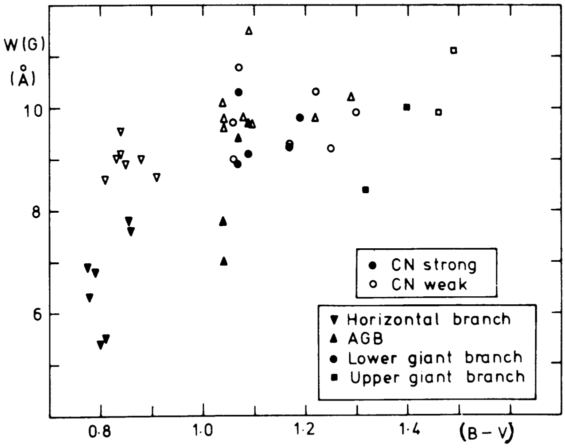

Fig. 5. The red giant branch, asymptotic giant branch, and horizontal-branch stars in the [W(G), (B-V)] - plane.

where W(G) is the equivalent width as illustrated in the upper right panel of Fig. 1. There is a clear anticorrelation, with CN strengthening accompanied by G-band weakening. The decrease in the effect at lower temperature may result from the effect of saturation as the G-band increases in strength. The simplest explanation of the anticorrelation is that the nitrogen enhancement inferred for the CN strong stars (Bell et al. 1975) is accompanied by a decrease in carbon, as might be expected from CNO processing.

To supplement our Ca line strength measurements we have obtained 33Å mm^{-1} spectra in the region of the MgI'b' lines for two CN strong and one CN weak red giants of similar magnitude and color, which are shown in Fig. 6. There is no obvious difference between the spectra, a result somewhat at odds with our Ca measurements.

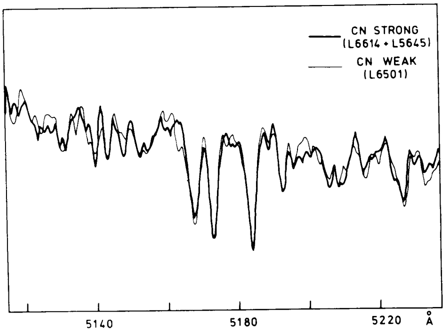

Fig. 6. Averaged spectrum of two CN strong stars compared with that of a CN weak star in the region of the MgI'b' lines. The three stars have very similar magnitude and color.

2.4 Discussion of the 47 Tuc Results

The CN and G-band results presented above seem to indicate that CNO processing plays an important role in the anomalies. The results for Ca and Mg are not so easy to interpret. Reference to the results of Gustafsson et al. (1975) shows, however, that interpretation of these features is made difficult by changes induced in atmospheric structure by CNO peculiarities. They find that CO and CN cause surface cooling and backwarming, respectively. In the CN strong, weak-G-band type of star found in 47 Tuc these effects will reinforce, leading to hotter outer regions. Further work is clearly necessary to evaluate the effects on CaII, MgI, and (B-V) before the effects seen in Figs. 4 and 5 can be fully understood.

We have argued above that if mixing is responsible for the observed anomalies, one is forced to postulate that it occurs below the level of the horizontal branch. While very mild CNO mixing is predicted at the base of the giant branch by stellar evolution computations (cf. Faulkner and Iben 1967) a more drastic effect is needed to explain nitrogen enhancements of a factor 10, as reported by Bell et al. (1975). Somewhat radical modifications to the above mixing process have been briefly considered by Norris and Zinn (1977) in the context of G-band weakening; following Dearborn, Bolton, and Eggleton (1975), they suggest that greater CNO mixing might occur as the result of thermal instability on the lower giant branch, together with substantial mass loss. The alternative, of course, is that the variations are primordial to the cluster, resulting from two (or more) epochs of star formation. The attractiveness of this hypothesis is that it requires no radical departures from reasonably well understood astrophysical processes.

3. THE TiO STARS IN ω CEN AND 47 TUC

It is not clear to what extent conclusions similar to those presented above apply to ω Cen. According to Freeman and Rodgers (1975) the abundances of some of the RR Lyrae stars in ω Cen are 47 Tuc-like ([Fe/H] ~ -0.5). Norris and Bessell (1977) found no counterparts of these stars in a sample of 60 red giants, while Glass and Feast (1973) noted that the TiO stars possess ultraviolet excesses unlike those in their 47 Tuc counterparts. The recent report by Lloyd Evans (1977) of further anomalously red members of ω Cen which appear to lie on the 47 Tuc locus in the [I,(V-I)]-plane allows us to further investigate this problem.

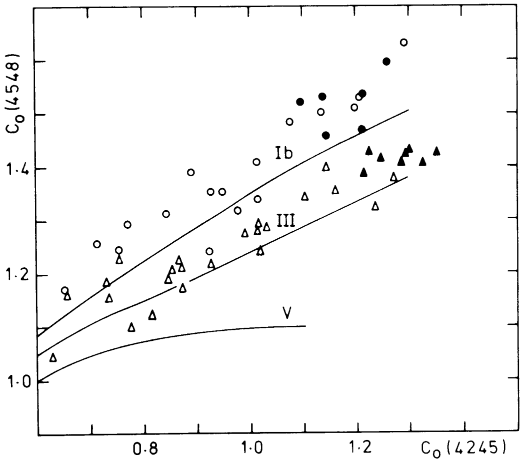

Fig. 7. ω Cen (circles) and 47 Tuc (triangles) red giants in the [C_o(4548), C_o(4245)]- plane. For ω Cen the filled circles represent the red stars of Lloyd Evans (1977); for 47 Tuc the filled triangles represent stars showing TiO bands.

We have obtained DDO photometry using the 1 m telescope at Siding Spring Mountain of several of the red ω Cen stars lying on the 47 Tuc locus (Lloyd Evans 1977, Fig. 1), together with several of the redder 47 Tuc stars. (Our spectra show TiO in both groups, though not in all ω Cen stars.) Our results, corrected for reddenings of E(B-V) = $0\overset{m}{.}11$ and $0\overset{m}{.}03$ for ω Cen and 47 Tuc, respectively, are shown in the $[C_0(4548), C_0(4245)]$- plane in Fig. 7, together with the results of Bessell and Norris (1975) for ω Cen, and McClure and Osborn (1974), Hesser et al. (1977), and Bessell and Norris (1977) for 47 Tuc. The Population I sequences of Osborn (1971) are shown also for comparison. In this plane we see a clear separation of the ω Cen red stars from those in 47 Tuc, lending support to the results of Glass and Feast (1973), and Norris and Bessell (1977) that few, if any, of the giants in ω Cen are like those in 47 Tuc.

These results do not necessarily argue against primordial abundance variations in ω Cen. One possible explanation is that large primordial CNO variations are responsible for most of the peculiarities observed in globular clusters and that in ω Cen these CNO variations are coupled with large heavy element variations (as a result perhaps of a very different mass function for its first generation of stars). With such peculiar abundance ratios it would be surprising if the ω Cen giants were 47 Tuc-like.

4. SUMMARY

CN variations have been found on the giant branch, the asymptotic giant branch, and the horizontal branch of 47 Tuc. In the outer regions 'strong' and 'weak' CN stars occur in roughly equal numbers on the three branches, while in the inner regions the 'strong' CN stars predominate.

CN strengthening appears to be accompanied by G-band weakening, suggesting that the CNO process plays a major role in the observed anomalies. The elements Ca and Mg give contradictory results; the CaII lines are stronger in the CN strong stars, while the MgI lines are unchanged. The effect of anomalous C, N, and O abundances on atmospheric structure may be responsible for this behavior.

We argue that mixing at the helium core flash or the helium shell flash provides an unconvincing explanation of these effects. If mixing is responsible one is forced to seek a site below the level of the horizontal branch. Given this situation a primordial origin of the peculiarities becomes more attractive.

Finally we show that the anomalous red stars in ω Cen (Lloyd Evans 1977) do not appear to be like the giants in 47 Tuc, as might have been expected from the abundances derived for the RR Lyrae stars in ω Cen. This places important constraints on any primordial origin of the peculiarities in this cluster.

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DISCUSSION

DEMING: I have computed synthetic spectra in the region of the 4150 Å CN absorption under the assumption of various types of CNO processing. It turns out to be difficult to produce a CN-strong star if one mixes only the products of hydrogen-burning. With conversion of carbon into nitrogen the CN bands remain constant in strength until more than about 60% of the carbon is processed into nitrogen. If larger fractions of carbon are processed into nitrogen the CN gets weaker due to the carbon depletion. It is possible to strengthen CN by also processing oxygen into nitrogen, but this requires high temperatures and densities. But even with the processing of oxygen into nitrogen some initial overabundance of oxygen is needed to produce the large nitrogen enhancements which the CN-strong stars require. If one admits that some carbon from helium burning may be present then it is much easier to make a CN-strong star.

NORRIS: The need for large nitrogen enhancement is also clear from the work of Bell, Dickens, and Gustafsson. Cottrell and I are performing computations similar to yours to obtain more information on the amount of nitrogen required in 47 Tuc.

KRAFT: That's quite a general problem - there's always too much nitrogen required. The nitrogen features are just too strong for the amount of processing from carbon you would expect, even if you process all of the carbon to nitrogen. In this mass range, I quess, you don't expect to get much O processed into N, and perhaps none at all.

TAYLER: I wish to suggest that we must learn something about primoridal abundance variations versus mixing in ω Cen from the fact that ω Cen has a very broad giant branch whereas other generally similar clusters do not. The star in the broadened giant branch must know that it is in ω Cen rather than another cluster. If it has a given mass and chemical composition, it will be equally affected by any mixing processes that occur, whichever cluster it is in. I therefore believe that we must ask what makes ω Cen different from other clusters. One possible solution, which has been suggested, is that ω Cen is sufficiently massive to retain significant quantities of heavy elements produced in a first generation of stars and this could then account for the variations in metal content. In any case we should be looking for some gross property of ω Cen which distinguishes it from other clusters.

NORRIS: ω Cen is distinguished also by two other properties. First, it has a large ellipticity. Second it has low concentration for its mass. McClure and I have recently noted that M22 shares these properties and (alone among the clusters investigated at that time) possesses CH, CN, and Ba II stars as found in ω Cen.

KRAFT: I would add that the spread also depends on the choice of color system you use and the type of "metal" causing the spread.

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