Carnegie Observatories Astrophysics Series, Vol. 4:
Origin and Evolution of the Elements, 2004
ed. A. McWilliam and M. Rauch (Pasadena: Carnegie Observatories,
http://www.ociw.edu/ociw/symposia/series/symposium4/proceedings.html)

Abundance Anomalies on the Main Sequence of Omega Centauri

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Abstract
We have obtained low resolution spectra from the Anglo-Australian Telescope's multifiber instrument (2dF) for $\sim$450 member stars at the main sequence and turnoff (MSTO) regions in the globular cluster ω Centauri. We have found a number of abnormal stars including CH, CN strong and s-process rich stars and have determined preliminary metallicities for the sample. These initial results are presented here.

1.1 Introduction

ω Centauri is the most massive globular cluster associated with our Galaxy and has been the subject of many studies due to its peculiar nature. With the large metallicity range in its member stars ($-1.8 \leq$ [Fe/H] $\leq$–0.4) ω Cen is not a typical globular cluster (Norris, Freeman & Mighell 1996; Suntzeff & Kraft, 1996; Pancino et al. 2000). It also has a possible age range (Lloyd-Evans 1977; Norris & Da Costa 1995; Smith, Cunha & Lambert 1995; Lee et al. 1999; Hughes & Wallerstein 2000; Hilker & Richtler 2000), and there is evidence for discrete populations within the system (Norris, Freeman, & Mighell 1996; Lee et al. 1999; Pancino et al. 2000).

ω Cen contains examples of red giant stars that are considered abnormal or unusual, including CH, barium and S stars (Lloyd-Evans 1983). There are two main possible scenarios to explain the formation of these stars. The first is that they formed by dredge up of material to the surface layers when the convective envelope deepens on ascent of the red giant branch, or from enrichment by companion or near-by AGB stars. The second scenario involves primordial enrichment of the gas cloud from which the star formed. To date there have been no detections of these types of stars below the subgiant branch of the cluster, perhaps simply due to the faintness of the objects in this region of the color magnitude diagram (CMD).

1.2 Observations

Photometry for the cluster was obtained on the 1m telescope and CCD combination at Siding Spring Observatory, in the V and B bands. Ten fields (20$\times$20 arcminutes), which overlapped slightly, were taken and the samples were chosen to be within an annulus 15 to 25 arcminutes from the center of the cluster. The resulting CMD is shown in the left panel of Fig. 1.1 and includes members of ω Cen as well as field stars. Two regions were defined near the MSTO. The first, Box 1, was chosen to determine the metallicity range on the upper main

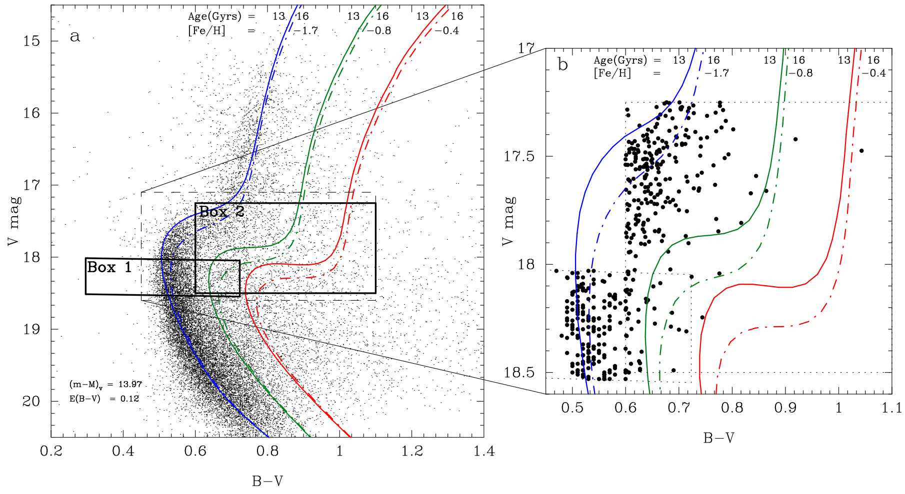

Fig. 1.1. Color Magnitude Diagram for ω Cen sample. The boxes on the left diagram show the two sample regions selected and the right panel shows the members resulting from 2dF observations of those samples. Overplotted are model isochrones from Bergbusch & VandenBerg (2001) for three different metallicities, [Fe/H] = –1.7, –0.8 and –0.4, with each having two ages separated by 3 Gyrs. A cluster reddening E(B–V) = 0.12 and distance modulus $(m–M)_v$ = 13.97 (Harris 1996) were assumed.

sequence. The second, Box 2, was defined to find the most metal-rich objects in that region, and also to obtain an age range for the cluster, since the age degeneracy of the isochrones for a given metallicity can best be broken at the turnoff region.

The samples were observed using the Two Degree Field Multiobject Spectrograph (2dF) on the Anglo-Australian Telescope. The 1200B grating was employed and the spectra obtained covered the wavelength range $\lambda\lambda$3800–4600Å. They have a resolution of $\sim$2.5Å FWHM.

The first sample was observed in May 1998 and April 1999, and the second in March 2002. This spectrograph has the capability of observing up to 400 objects at once. Due to the high density of ω Cen and its relative size compared to the two degree field of view, the average number of objects observed in a given field was $\sim$180. Each field was observed for a short amount of time ($\sim$ 1–2 hrs) to achieve low S/N ($\sim$10) for each object. The data were reduced at the telescope using the standard 2dF reduction package and membership classification was given to stars with a radial velocity, within acceptable errors, close to that of ω Cen's ($\sim$230kms^{-1}). The members were then reobserved ($\sim$ 3–5 hrs) to obtain higher S/N spectra ($\sim$ 30–50) for more detailed analysis. The first and second samples were observed to completeness levels of 37% and 94% respectively, where the completeness level is defined as the number of objects observed to the number that could have been observed. To be classed as "observable" each star underwent a visual inspection on the CCD images to ensure there were no contaminating objects within five arcseconds. This process yielded a final sample of $\sim$450 members at the (MSTO) region of ω Cen as shown in the right panel of Fig 1.1. It is clear that there are main sequence members of ω Cen with [Fe/H] $\geq$ –0.8, although more analysis is needed to unravel any age/metallicity relation.

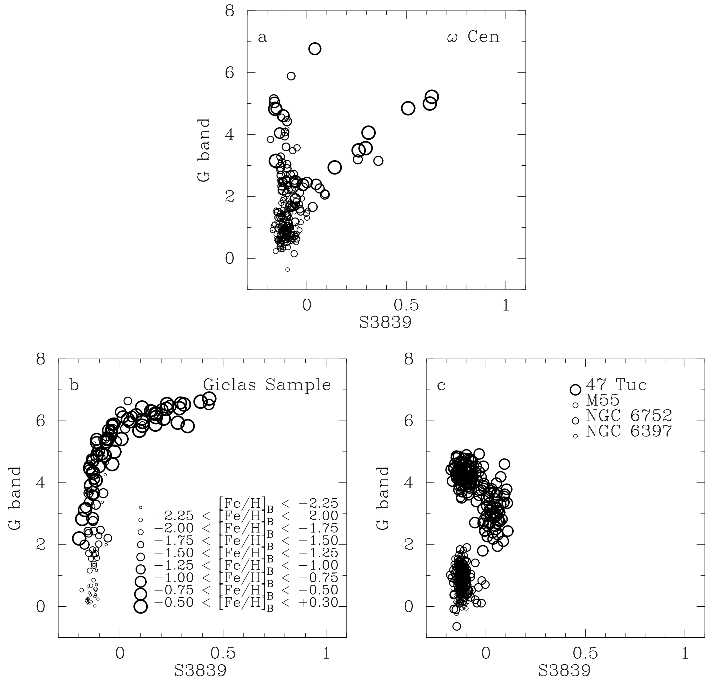

Fig. 1.2. The distribution of CH (G band) and CN (S3839) indices (as described in the text) for ω Cen, Giclas high-proper-motion stars, and members of four "normal" globular clusters – 47 Tuc, NGC 6752, M55 and NGC 6397. The points represent metallicity indicated by their size – the larger the symbol the higher the metallicity.

1.3 Results

Metallicities were obtained for the ω Cen sample using the Ca II K line index and B–V color in the calibration developed by Beers et al. (1999). These abundances are only accurate to $\sim$0.2–0.3 dex due to the resolution and S/N of the data and the fact that the metallicity calibration does better at low metallicities than high ones. In Figures 1.2 and 1.3 the metallicity is indicated by the size of the symbol – the larger the symbol the higher the metallicity. The following sections give details of the analysis on the CH and CN features (§1.3.1) and the strontium (λ=4077Å) and CN features (§1.3.2).

1.3.1 CN and CH

The cyanogen (CN) band at $\sim$3883Å is measured using the definition of Norris et al. (1981) and is denoted S3839. The G band was measured using a line index similar to that of Beers et al. (1999) with an on-feature band width of 25Å. Measurements were made also on a sample of Giclas high-proper-motion stars (chosen from Carney et al. 1996, and observed with the 2.3m telescope on Siding Spring) and members from other globular clusters (47 Tuc, NGC 6752, M55 and NGC 6397) for comparative purposes. These relatively normal globular clusters bracket the main populations of ω Cen in metallicity.

Fig. 1.2a shows the G band line strength versus the cyanogen index for ω Cen. This is only for stars fainter than V = 18, to compare the relatively unevolved stars in ω Cen with those from the normal globular clusters and Giclas stars. There is an obvious dichotomy in

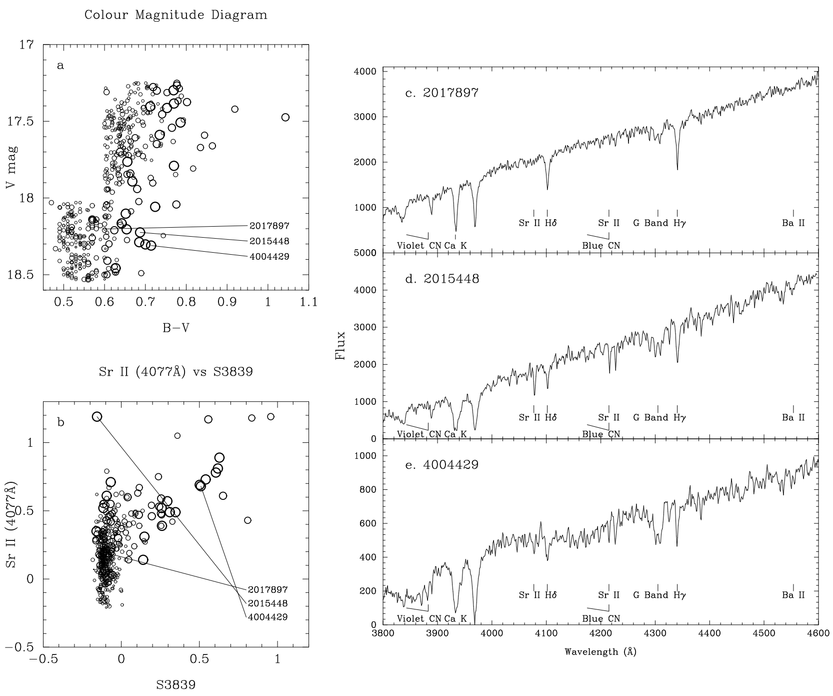

Fig. 1.3. Top left panel is a color magnitude diagram showing the member stars with symbols coded for metallicity. Bottom left panel shows the Sr II 4077Å index plotted against the cyanogen index. The features can be seen in the spectra in the right panel. See text for details.

the distribution of the points. Figures 1.2b and 1.2c show the results for the same analysis performed on the Giclas sample and the calibrating globular clusters. The Giclas stars seem to correspond well with the upper branch in the ω Cen results. There is a large range in G-band strengths with very little detectable change in CN until higher metallicities are reached, where the CN starts to increase rapidly.

The anti-correlation between CN and CH is well documented in 47 Tuc (Norris & Freeman 1979; Cannon et al. 1998) and can be seen in Fig. 1.2c. It is conceivable that the low-CH, high-CN "clump" in 47 Tuc could provide a partial explanation for the lower branch seen in the ω Cen diagram. The mechanism that drives the bimodality in 47 Tuc is thought to be unique to globular clusters. This is further shown by the absence of the bimodality in the Giclas sample. However, the bifurcation seen in the ω Cen sample is much more extended that in 47 Tuc, which may be due to the higher metallicity of some of the ω Cen stars. This bifurcation is not seen in the other globular clusters – NGC 6752, 6397 and M55. The stars from these clusters occupy a relatively small area on the diagram indicating little or no detectable range in carbon or nitrogen.

1.3.2 Strontium and Cyanogen

Figures 1.3a and 1.3b have metallicity represented by the size of the symbols (as in Fig. 1.2). The strontium line index is a pseudo equivalent width defined in a similar manner to the G-band index described earlier, with an on-feature band width of 6Å. The Sr II (4077Å) vs S3839 plot shows that the main group of ω Cen stars has little CN enhancement, while the objects that have an enhancement in CN also tend to show strong Sr features.

Three spectra of main sequence stars are shown to the right of the figure. The first (Fig. 1.3c) is one of the most frequent type of star and is classified as "normal". It shows no enhancements of CN or Sr, and has no unusual features. Fig. 1.3e is a spectrum of a star that shows enhancement in Sr and in CN – seen by the large molecular absorption bands. This object is typical of the trend in enhancements in both CN and Sr seen in Fig. 1.3b.

Fig. 1.3d shows the spectrum of an object that stands well away from the trend in Fig. 1.3b. This star has $[Fe/H]_k \approx -0.2$ and shows a large enhancement in Sr, but none in CN. There also does not seem to be any enhancement for barium in this star. This particular result is confirmed by three independent spectra, taken at widely spaced epochs. Work by Norris and Da Costa (1995) indicates that stars that enriched proto ω Cen were s-process enhanced. From their work and that of Norris, Ryan & Beers (1997) one would expect that for the metal abundance of this star [Ba/Fe] should be similar to [Sr/Fe] – which is clearly not the case. Spectrum synthesis for this object shows that an enhancement factor of $\sim$100 for Sr is needed to explain the high absorption, while a similar enhancement of Ba predicts a much stronger Ba II 4554Å line than is observed. Further work on this star is in progress.

1.4 Conclusions

The wealth of information obtained for this MSTO sample in ω Cen is only just beginning to be investigated, but already it is indicating some very interesting results. There exist stars on the MSTO areas that exhibit enhancements of CH and CN similar to those observed on the RGB and the spread in metallicities in both regions is comparable. Not only can this sample give us evolutionary clues to the formation and enrichment of ω Cen, but along with the other globular clusters it may also shed some light on the formation and evolution of relatively normal globular clusters.

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