Mem. S.A.It. Vol. 75, 370

Memorie della

Globular Cluster Abundance Anomalies: Clues from the Main Sequence

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Abstract. We present an analysis of spectra of a large sample of main sequence stars in the globular cluster 47 Tuc observed with the 2dF multi-fibre instrument on the Anglo-Australian Telescope. The spectra confirm that anti-correlated variations in the strengths of the CN and CH bands exist among the main sequence stars in this cluster. Further, the ratio of CN-strong to CN-weak stars on the main sequence is identical, to within the statistics, to the value for the red giant branch. This strongly implies that evolutionary (mixing) processes do not play a significant role in generating the abundance anomalies observed in this cluster. We also find that the strengths of the sodium-D lines in the spectra of these main sequence stars correlate positively with the cyanogen band strength index. We then compare our 47 Tuc results to those for main sequence stars in M71, a globular cluster of comparable abundance to 47 Tuc, and to those for main sequence stars in the more metal-poor globular cluster M13.

1. Introduction

For almost three decades now, the abundance variations seen in the elements O, C, N, Na, Al and Mg among the stars in most, if not all, globular clusters have lacked a complete and comprehensive explanation. The hypotheses that have been advanced to explain the anomalies can be grouped into two broad classes: those in which the anomalies arise from processes internal to the stars, here referred to as *mixing* hypotheses, and those in which the anomalies arise from external processes, the so-called *primordial* processes. In the past, most observations related to globular cluster abundance anomalies have been restricted to stars brighter the main sequence turnoff. However, the cluster main sequence is a natural location to try to constrain the relative importance of these two processes for one simple reason: in a main sequence star it is difficult to see how the abundance anomalies could be produced by internal mixing processes.

The reasons for this are as follows. In a main sequence star the energy generation occurs in the very central regions, so that any processing (e.g. CNO cycling) necessarily occurs in the deep interior. Mixing processed material all the way to the surface layers would then effectively mix the entire star, bringing fresh

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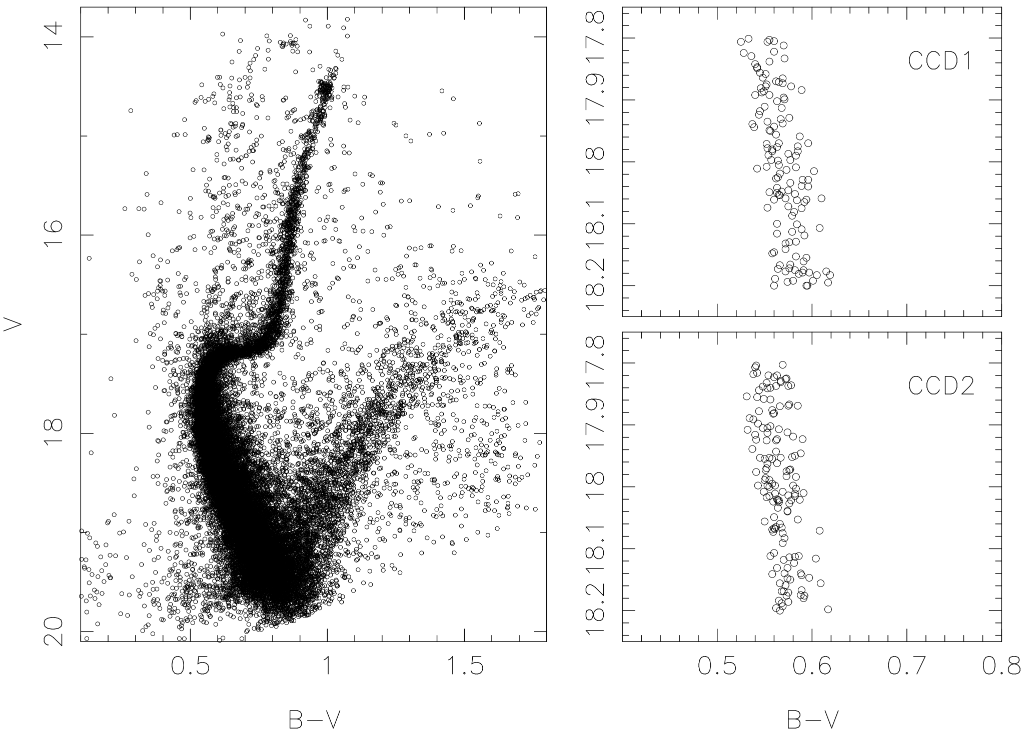

Fig. 1. *Left Panel:* a colour-magnitude diagram for 47 Tuc based on CCD observations obtained with the 1m telescope at Siding Spring Observatory. The SMC giant branch is also visible. *Right Panels:* photometry for stars observed with 2dF. Stars with discrepant radial velocities or CaII line strengths have been excluded.

hydrogen to the central regions. Stars with such quasi-homogeneous composition evolve along the main sequence and do not 'turnoff' in the way non-homogenous (i.e. standard) evolving stars do. Consequently, if such a main sequence mixing process did occur, a spread in luminosities and temperatures would be expected at the main sequence turnoff, in distinct contrast to the narrow sequences observed in all clusters. Thus, if abundance anomalies are observed among the main sequence stars in a given cluster, it argues rather strongly for a primordial origin for those abundance anomlies. Of course, this does not mean that mixing processes in the post-main sequence stars in the cluster are ruled out.

In this contribution we concentrate initially on results for main sequence stars in 47 Tuc, a relatively metal-rich, high luminosity southern globular cluster that has been a prime target for observations in this subject field for decades (cf. Norris & Freeman (1979)). Some of the results have already been reported in Cannon et al. (2002) and Cannon et al. (2003). In the subsequent section we review results for main sequence star abundance anomalies in some other clusters and, in the final section, draw some brief conclusions.

2. 47 Tucanae

We begin by mentioning some relatively recent results on abundance anomalies in main sequence stars in this cluster. Briley et al. (1994), drawing on earlier work, observed that for a relatively modest sample of stars near the main sequence turnoff, the distribution of λ3883Å CN-band strengths was bimodal. There was also some indication of an anti-correlation between the CN-band strengths and those of the G-band (CH). For 3 pairs of CN-strong and CN-weak stars, Briley et al. (1995) also observed that the CN-strong stars had stronger Na-D lines, corresponding to a sodium abundance enhancement in the CN-strong stars of ~0.25 dex. However, of these three pairs, strictly only one pair is actually fainter than the cluster main sequence turnoff, and for this pair there is no apparent Na abundance difference.

Subsequently, Cannon et al. (1998) also observed a sample of main sequence stars in this cluster, and despite the relatively low signal-to-noise of their spectra, they were able to conclude that there is indeed a bimodal distribution of CN-band strengths on the main sequence, and a CN–CH anti-correlation. By applying spectrum synthesis techniques, Cannon et al. (1998) concluded that the CN-strong stars were enhanced in nitrogen by a factor of ~7 and depleted in carbon by about 40 percent. However, there were no observations of the Na-D lines.

Finally, Harbeck et al. (2003) have used the VLT to observe a sizeable sample of stars in 47 Tuc, with the stars stretching from just brighter than the turnoff to ~2.5 mag below it. Once again a bimodal distribution of λ3883Å CN-band strengths is observed, with the 'gap' between the two groups increasing for fainter stars. Such an effect is not unexpected: the fainter stars are also cooler and thus will have a larger molecular band strength difference for a given C and N abundance difference. Harbeck et al. (2003) also saw some indication of a CN–CH band strength anti-correlation, but were not able to make any comments about potential Na abundance differences between the two groups.

Our data consist of observations of a large sample (~280 stars) of 47 Tuc main sequence stars made with the 2dF multi-fibre spectrograph at the Anglo-Australian Telescope. For the first set of observations, we used a blue grating to cover spectral features such as the λ3883Å CN-bands, the H and K lines of CaII and the G-band (CH). For the second set, we used a red grating and observed the same sample of stars at the Na-D lines. Both sets of spectra are of relatively high signal-to-noise (e.g. S/N > 30 at the G-band) and have a resolution of ~2.7Å. The 2dF fibres feed two separate spectrograph - detector combinations that have slightly different characteristics. Consequently, we have kept these 'spectrograph 1/CCD 1' and 'spectrograph 2/CCD 2' samples separate in the following analyses. The left panel of Fig. 1 shows a colour-magnitude diagram for the cluster based on CCD observations taken with the 1m telescope at Siding Spring Observatory. The right panels show the corresponding photometry for those stars observed with 2dF that are probable cluster members. We exclude from these panels, and from the subsequent discussion, a small number of stars that have discrepant radial velocities, and/or CaII line strengths, relative to the probable cluster members.

In Fig. 2, we show the distribution of CN-band strengths for these main sequences stars using the S(3839) band strength indicator. The upper panels show the band strength as a function of V magnitude. The middle panels show binned histograms for the CN-strengths, and the lower panels show generalized histograms from the same data. The distributions are clearly bimodal and a CN-strong/CN-weak division at S(3839) = 0.10 has been adopted. Fig. 3 shows a plot of an index of CH-band strength against the CN-band index. A definite anti-correlation between these two band strength indices is clearly present in both samples. Preliminary spectrum synthesis calculations show that the C and N abundance differences between the two groups are similar to those found by Cannon et al. (1998): the CN-strong stars have N abundances a factor of ~7–10 higher, and C abundances a factor of ~2–2.5 lower, relative to the CN-weak stars. There is no evidence in these blue spectra for variations in any elements other than C and N. This is graphically illustrated in Fig. 2 of Cannon et al. (2003) where a high signal-to-noise CN-strong spectrum, made by adding together the spectra of a large number of individual CN-strong stars, has been divided by an equivalent high signal-to-noise CN-weak spectrum. The only features that remain in the divided spectrum are those due to CN and CH; all other feature, in-

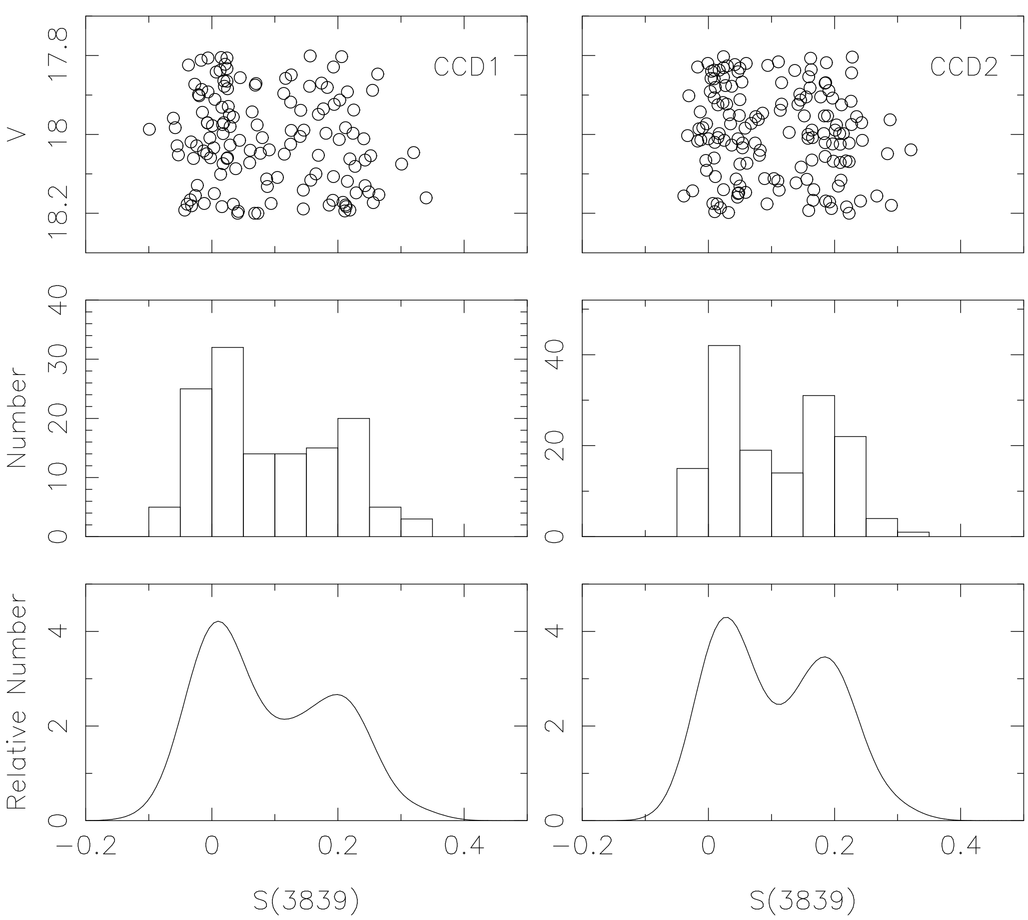

Fig. 2. Distributions of S(3839), the band strength index for the λ3883Å CN-band. The upper panel shows the *V* magnitudes of the stars while the middle and lower panels show binned and generalised histograms, respectively. The bimodal nature of the distributions is evident.

cluding the CaII H and K lines, cancel out to a remarkably high precision.

In the combined spectrograph 1 and spectrograph 2 2dF samples there are 129 CN-strong stars and 152 CN-weak stars, for a combined CN-strong to CN-weak ratio on the cluster main sequence of 0.85 ± 0.10 (assuming Poisson statistics). We now seek to compare this ratio with that for the red giant branch, in order to test for any change with evolutionary phase. The largest available sample of CN-band strengths for 47 Tuc red giants is that compiled by Paltoglou (1989), which includes the earlier samples of Norris & Freeman (1979) and Norris et al. (1984). In this red giant sample, the ratio of CN-strong to CN-weak stars shows a radial gradient, with increasingly more CN-strong stars towards the cluster centre (cf. Norris & Freeman (1979)). However, beyond 6′ from the cluster centre, which is the region of the 2dF main sequence sample, the CN-strong to CN-weak red giant ratio is constant (Paltoglou 1989). Further, in this region, there are 91 CN-strong stars and 118 CN-weak stars for a number ratio on the red giant branch of 0.77 ± 0.11 (again using Poisson statistics). The agreement between the CN-strong to CN-weak ratio on the main sequence with that

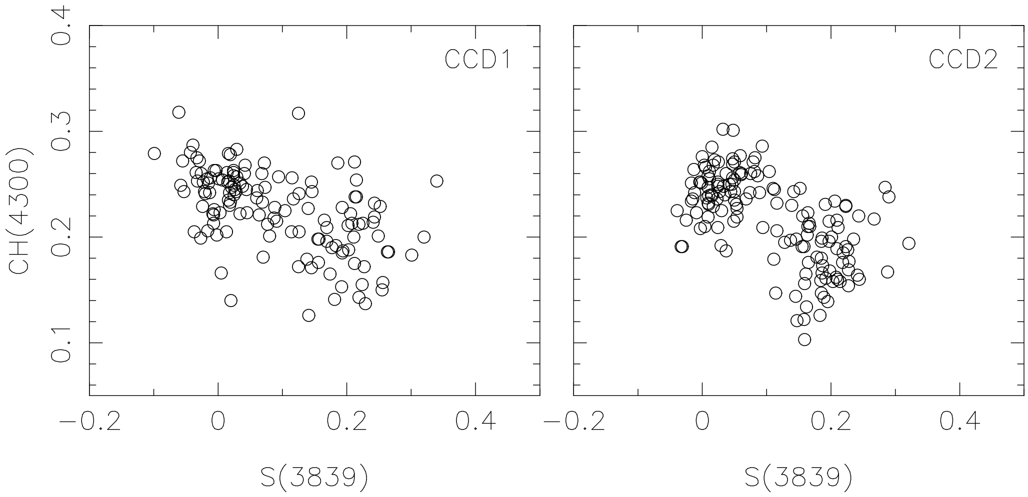

Fig. 3. A plot of the G-band (CH) strength index CH(4300) against the cyanogen band strength index S(3839) for the 47 Tuc main sequence stars. The two indices appear anti-correlated.

on the red giant branch *strongly suggests that there are no evolutionary mixing effects in the origin of the C and N abundance anomalies in this cluster*.

In Fig. 4, we show a plot of the strengths of the sodium D lines against the CN-band strength index S(3839). We note that because of the relatively low heliocentric velocity of 47 Tuc, a successful measurement of the Na-D line strengths in the stellar spectra requires accurate subtraction of the Na-D night sky emission lines. This is not always possible and, as a result, the uncertainty in the W(NaD) values is larger than it would be for an uncontaminated feature of the same strength. Nevertheless, it is apparent from the panels of Fig. 4 that the Na-D line strength for these 47 Tuc main sequence stars is positively correlated with the CN-band strength index S(3839). Quantitatively, if we separate CN-strong and CN-weak stars at S(3839) = 0.10 (cf. Fig. 2), then for spectrograph1/CCD1 the 55 CN-strong stars have a mean W(NaD) value of 1.415 ± 0.018 while the 64 CN-weak stars have a mean W(NaD) of 1.267 ± 0.023. The difference is then more than 5 times the combined error. For spectrograph2/CCD2, the corresponding values are 1.499 ± 0.028 (64 CN-strong stars) and 1.395 ± 0.023 (60 CN-weak stars) and the difference is just under 3 times the combined error.

Preliminary analysis of these Na-D line strength differences suggests that the sodium abundance difference between the CN-strong and CN-weak populations is somewhat less than the ~0.25 dex found by Briley et al. (1995) for their 3 CN-strong/CN-weak pairs. The rather limited data available for 47 Tuc red giants also suggests a ~0.3 dex sodium abundance difference between the CN-strong and CN-weak stars (Cottrell & Da Costa 1981; Brown & Wallerstein 1992).

We need to complete our analysis before drawing any conclusions here. However, one question will remain unanswered for the present: *presumably all the CN-weak stars have the same Na abundance, but is this also true for the CN-strong stars?* An answer to this question, or at least limits on any possible Na abundance variation within the CN-strong population will aid substantially in understanding the possible origins of the abundance anomalies. For example, it is not at all clear whether 47 Tuc stars, be they red giants or main sequence stars, follow the sodium-oxygen anticorrelation prevalent in more metal-poor clusters.

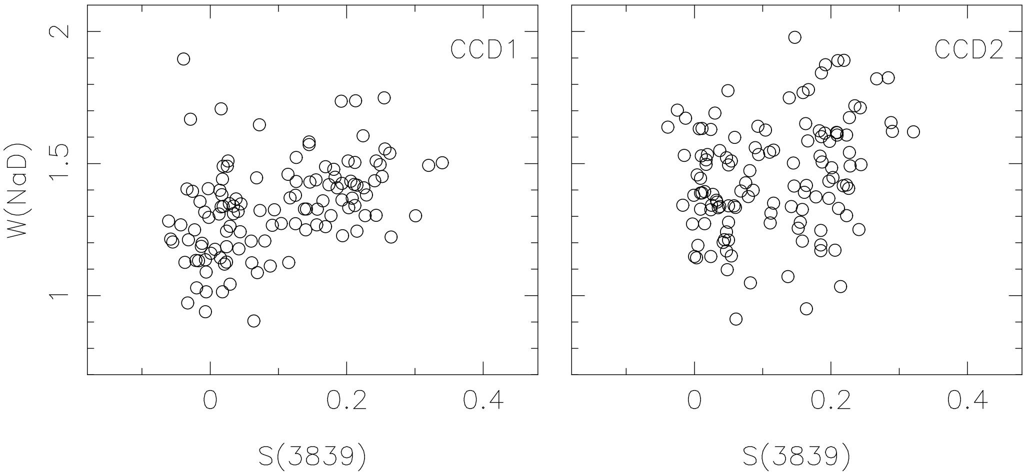

Fig. 4. A plot of Na-D line strength index W(NaD) against cyanogen band strength index S(3839) for the 47 Tuc main sequence stars. The two indices appear positively correlated.

3. Other Clusters

Gratton (these proceedings, see also Gratton et al. (2001)) has discussed results for main sequence stars in a number of clusters (e.g. NGC 6752 and NGC 6397) and these will not be repeated here. Instead we will concentrate on M71, a globular cluster of similar overall abundance to 47 Tuc, and on M13, a cluster of intermediate metal-poor abundance.

For M71, Cohen and collaborators (e.g. Briley & Cohen (2001)) have shown that this cluster is very similar to 47 Tuc, at least as regards CN and CH. In particular, for stars on the main sequence, to first order both the CN and CH band strength indices have bi-modal distributions, and are anti-correlated. Briley & Cohen (2001) also show that the band strength indices can be fit with (CN-strong – CN-weak) abundance differences of Δ[N/Fe] = +1.0, Δ[C/Fe] = –0.3 and Δ[O/Fe] = –0.3 dex, respectively. These abundance differences are those found for the red giant branch (Briley et al. 1997, 2001; Sneden et al. 1994). The relative number of CN-strong and CN-weak stars on the main sequence is also very similar to what is found on the red giant branch. Thus, like 47 Tuc, there is little evidence for any mixing or evolutionary effects in this cluster.

However, when we look at more metal-poor clusters, the situation is not as clear-cut. For example, Briley et al. (2002) have investigated carbon abundances as a function of evolutionary state in the intermediate metallicity cluster M13. As shown in their Fig. 1, Briley et al. (2002) find a substantial range (factor ~6) in [C/Fe] for stars fainter than the main sequence turnoff[1]. This large range in C abundance is suggestive of a primordial process occurring in this cluster. However, the mean [C/Fe] value decreases from the subgiant branch to the tip of the red giant branch. Such an evolutionary change can only be explained as an internal mixing process. Thus in this cluster, it would seem that *both* primordial *and* mixing processes are important.

4. Conclusions

Based on the available observations, it seems that in the relatively metal-rich clusters like 47 Tuc and M71, evolutionary mixing processes don't play any substantive role and we must look to a primordial process to explain the abundance anomalies. On the other hand, it appears that in the metal-poor clusters both

[1] These stars are too hot and of too low an abundance for measureable CN-band strengths.

primordial and mixing processes are occurring, with the mixing beginning not much beyond the turnoff, perhaps at the base of the giant-branch when the star reaches the Hayashi boundary.

However, while such a picture is inferred from the observations, we are still a long way from any understanding of the physical processes involved. For instance, in the primordial hypothesis, in any model of globular cluster formation, can we restrict the anomalies to just those observed *and* maintain a high degree of chemical homogeneity for the heavier elements like Fe and Ca? It's frequently been suggested that there may be a role for the ejecta from upper-AGB stars in forming the CN-strong, Na-strong, C-weak, O-weak stars, but we need to attack this quantitatively to see if it is possible. The calculations of Smith & Norris (1984) suggest that this will be no easy task. Similarly, standard evolutionary models don't predict the type of deep mixing seen on the red giant branch. While modifications can be made to force such mixing, it is not by any means clear why such a mechanism should be specific to cluster stars – recall that field red giants do not show these anomalies to anything like the same extent (e.g. Langer et al. (1992)). Clearly this problem will be with us for a while yet!

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