Spectroscopy of Main Sequence Stars in Globular Clusters

Russell Cannon

Anglo-Australian Observatory, PO Box 296, Epping, NSW 2121, Australia

Gary Da Costa, John Norris, Laura Stanford

Research School of Astronomy & Astrophysics, Australian National University, Mount Stromlo Observatory, Cotter Road, Weston, ACT 2611, Australia

Barry Croke

Integrated Catchment Assessment & Management Centre, and Centre for Resource & Environmental Studies, Australian National University, Canberra ACT 0200, Australia

Abstract. Although globular clusters are generally chemically homogeneous, substantial abundance variations are sometimes seen even among unevolved main sequence stars, especially for the CNO group of elements. Multi-object intermediate-dispersion spectroscopic systems are now being used to determine the patterns of abundance variations for large samples of stars, while high dispersion spectrographs on 8m-class telescopes are providing good spectra of individual faint stars. In some circumstances the spectra of many similar stars can be combined to yield extremely high S/N spectra. The sample of clusters which has been studied remains small, but it seems that many of the more metal-rich clusters must have experienced some sort of self-enrichment, either in a proto-cluster stage, or through successive episodes of star formation or some other processes early in their lives. The metal-poor clusters provide equally clear evidence for internal mixing and dredge-up of processed material within evolving red giant stars.

1. Introduction

This meeting is in honour of Ivan King, who has led the way in many aspects of star cluster research. Although he has not, so far as I am aware, done very much spectroscopic work, we might be in better shape today if he had. The same principles which he and his colleagues have applied so effectively in the careful analysis of HST astrometry and photometry apply equally in the field of spectroscopy with ground-based telescopes. We are now in the happy position of being able to obtain good high dispersion spectra of tens of stars, or intermediate dispersion spectra for hundreds of cluster stars, using fibre-fed multi-object spectrographs on large telescopes. As a result we are no longer limited by the low
signal-to-noise ratio (S/N) of individual spectra or by small number statistics. However, we are encountering new difficulties and are often limited by systematic errors or calibration problems. The complexity of modern instruments also means that observers often have to treat the control and data-analysis systems as ‘black boxes’. The result is that although we can obtain vast amounts of data rather quickly and easily, to analyse them carefully is still as time-consuming as ever, and requires the combined skills of teams of people with complementary expertise. To finally understand what we observe remains the hardest and slowest step.

The old assumption that all the stars in a given cluster have about the same chemical composition and age remains a valid first approximation today, as shown by the very well-defined sequences in the best colour-magnitude diagrams (CMDs). There is one glaring anomaly, ω Centauri, which certainly has a wide spread in metallicity (by more than a factor of ten) and possibly a wide range in star formation epoch; this cluster was the topic of an entire meeting just one year ago (van Leeuwen, Hughes & Piotto, 2002). However, for most well-observed globular clusters any spread in the abundance of iron or other heavy elements is below the level of detectability. Similarly, there is no evidence for significant internal age spreads, although here the limits are generally at the level of about 1-2 Gy or 10% of the age of the clusters, so there is scope for some initial spread in star formation.

The situation is however very different for some of the lighter elements, especially C, N and O, and a few related species including Na, Al and Mg. Large variations in the strength of features due to CN and CH were first noted more than 30 years ago (see e.g. the reviews by Freeman & Norris, 1981 and Kraft, 1994). Initially these were seen in bright red giants and were generally assumed to be due to the dredge-up of processed material from the cores of the stars. There is good evidence that such processes do occur, especially in very metal-poor clusters. However, the CNO variations often persist down on to the main sequence (m.s.) (e.g. Hesser, 1978), where neither the requisite nuclear reactions nor the mixing mechanisms are supposed to occur. It seems that some stars contain substantial amounts of material which have been processed through the CNO cycle in more massive stars, and that there may have been an extended period of star formation or some other processes of self-enrichment and accretion during the early life of the clusters.

There are two main strands to recent work: observations of large samples of stars using multi-object systems, and higher dispersion spectra for smaller samples. We concentrate more on the former, because others here (Gratton, 2002; several poster contributions) deal with the latest VLT and Keck results. We have obtained spectra for a few hundred main sequence turn-off (MSTO) stars in each of 47 Tuc, NGC 6752 and ω Cen, using the 2dF facility on the AAT (Lewis et al, 2002). Total exposure times were about 4 hours for each sample of ∼300 stars, yielding spectra with S/N ∼ 30 per pixel and a resolution of about 3Å. Two spectral regions were covered, blue spectra extending from 3700Å to 4800Å and red spectra centred on the Na D lines at 5900Å. More details of the observations are given in Cannon et al (2002).

It is convenient to group the clusters since those with similar metallicities seem to show similar CNO abundance patterns. However, it is not yet clear
whether this signifies a real metallicity dependence or merely reflects the most easily observable effects, or indeed if it is simply an accident of the small number of clusters studied so far.

2. Relatively metal-rich clusters with $[\text{Fe/H}] \sim -0.8$

2.1. CN and CH in 47 Tuc

The individual 47 Tuc blue spectra show obvious variations in the strengths of the CH band near 4300Å and the UV CN band near 3880Å, although the latter feature is harder to assess visually due to the converging Balmer series of H lines and other features. To provide a quantitative measure we use simple band strength indices. The result for one sample is shown in Fig. 1. There is a clear anti-correlation between the strengths of CN and CH and the distribution appears to be bi-modal, at least in the more sensitive CN index. Both of these features are qualitatively the same as seen in the red giants in 47 Tuc (Norris & Freeman, 1979). The bi-modality may be to some extent an artefact of non-linearity in the formation of the molecular bands (Langer, 1985) but synthetic spectra show that there is certainly a large range in the abundances of C and N.

We can split the sample in two according to CN strength and produce two very high S/N spectra with about 200 hours of exposure each. Figure 2 shows (a) the mean spectra for some 50 CN-strong stars and 80 CN-weak stars, and (b) the result of dividing one by the other. The UV CN absorption shows up very strongly in the quotient spectrum, while the anti-correlated CH G-band appears in ‘emission’, along with some broader features extending from 4200Å to 4450Å. The CaII H & K lines, which are the strongest features in the original spectra, have cancelled almost perfectly, as have the Balmer series H lines and
other absorption lines due to Fe, CaI and other species. This accurate cancellation shows that the two samples of 47 Tuc stars must have almost exactly the same mean effective temperature, surface gravity and heavy element abundances. It appears that the two samples of stars vary only in their surface C and N abundances.

In order to quantify the difference in C and N abundances we have made synthetic spectra to match the 47 Tuc stars, using the \textit{ssg} code of Bell & Gustafsson (1978) and MARCS model atmospheres (Gustafsson et al. 1975). The best fit is obtained with a pair of models having overall \([\text{Fe/H}] = -0.7\), one having \([\text{C/Fe}]\) and \([\text{N/Fe}]\) close to the solar values and the other with C depleted by a factor of 2.3 and N enhanced by a factor of 10. The synthetic ‘quotient spectrum’ is plotted in the lower panel of Fig. 2. There is very good agreement with the observed quotient spectrum, both in terms of the overall strength of the molecular bands and their detailed structure. The numerical values of the C and N abundances are close to those derived previously for much smaller (and lower S/N) samples of m.s. stars in 47 Tuc by Briley et al. (1996) and Cannon et al. (1998), and to the abundances seen in the evolved red giants.

Very recently Harbeck, Smith & Grebel (2002) obtained VLT spectra for a sample of 115 m.s. stars in 47 Tuc. These extend more than 2 mag fainter than
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2.2. Sodium in 47 Tuc

The individual red AAT 2dF spectra show few features apart from the Na D doublet at 5900 Å. The result of combining the spectra of the same 50 CN-strong stars as before is shown in Fig. 3. Many fainter absorption lines appear, most of them due to iron. Some residual night sky features are seen from strong [OI] emission lines at 5577 Å, 6300 Å and 6363 Å; these have not cancelled perfectly because of their high intensity and small variations in the point spread function of the images in the 2dF spectrographs.

When the mean red CN-strong spectrum is divided by the mean red CN-weak spectrum, the only real features which remain are the Na D lines in absorption. Evidently the Na absorption is correlated with the N enhancement, as found by Cottrell & Da Costa (1981) for red giants, and by Briley et al. (1996) for a sample of six m.s. stars in 47 Tuc.

2.3. M71

M71 has about the same metallicity as 47 Tuc but is much less massive ([Fe/H] = −0.8; $M_v = −5.6$ cf. −9.4 for 47 Tuc). Briley & Cohen (2001) have obtained spectra for a sample of stars near the MSTO. They find very similar results to those reported here for 47 Tuc, i.e. a strongly bi-modal distribution of CN band strengths, anti-correlated with CH. This similarity removes the previous worry that perhaps 47 Tuc is atypical, being one of the most massive globular clusters and with a very concentrated core. In another recent result based on the same Keck spectra, Ramirez & Cohen (2002) have found that there are no measurable differences in the iron abundances of stars across the CMD of M71.
3. Intermediate-metallicity clusters, with $[\text{Fe/H}] \sim -1.4$

3.1. NGC 6752

The red giants in NGC 6752, like those in 47 Tuc, show bi-modal CN variations which are anti-correlated with CH (Norris et al., 1981). However, the overall metallicity of NGC 6752 is about 4 times lower than in 47 Tuc, so the molecular bands in MSTO stars are much weaker because of both the lower abundance and the higher temperature; the abundance effect is doubly severe in the case of CN. Synthetic spectra show that this is indeed the case: the bands have similar structure to those in 47 Tuc, but the features are 10-20 times weaker.

The same technique of combining spectra for many faint stars can be used, but this time using the stronger CH G-band to divide the sample. In NGC 6752 the quotient spectrum again shows UV CN absorption anti-correlated with the CH feature, but the detection is rather marginal and it is impossible to say whether the distribution is bi-modal.

Independent evidence for main-sequence abundance variations in NGC 6752 comes from recent high-dispersion VLT spectra for a small sample of stars by Gratton et al. (2001). They find that the oxygen and sodium abundances are anti-correlated, while the Fe abundance remains fixed at the same value across the CMD.

3.2. M5

Cohen, Briley & Stetson (2002) have used LRIS on Keck to obtain low-dispersion spectra for more than 40 stars near the base of the red giant branch in M5, the largest uniformly observed sample of stars near the base of the giant branch in any cluster. They find strongly anti-correlated variations in CN and CH, although no evidence for bi-modality. By contrast, Smith & Norris (1983) found a strongly bi-modal CN distribution, again anti-correlated with CH, for 29 brighter giants in M5.

4. Metal-poor clusters, with $[\text{Fe/H}] \sim -2.0$

The red giants in several low-metallicity clusters provide convincing evidence of the dredge-up of internally processed material to the surface (e.g. Langer et al., 1986 for M92; Briley et al., 1990, for NGC 6397). It will probably be impossible to detect the CN bands in turn-off stars in such metal-poor clusters. However, recent high resolution spectra taken with the ESO VLT for m.s. stars in NGC 6397 ($[\text{Fe/H}] \sim -2.1$) by Gratton et al. (2001) show that the O and Na features remain constant in this cluster, as they do among the giant stars, in contrast to the anti-correlated pattern seen in NGC 6752. No results for C or N have been reported as yet, but in another study of the same set of 12 spectra, Bonifacio et al. (2002) find that all the stars have the same Li abundance, at a level which is about equal to the primordial ‘Spite plateau’. On the other hand, Boesgaard et al. (1998) do find a significant spread in Li abundance from Keck spectra for 7 m.s. stars in M92.
5. The special case of $\omega$ Centauri

While the majority of $\omega$ Cen stars are metal-poor with [Fe/H] $\sim -1.7$, it has red giant and m.s. members whose metallicity extends to well above $-1.0$. Recently, Lee et al. (1999) and Pancino et al. (2000) discovered a very red, high metallicity component of the giant branch in $\omega$ Cen. If this comes from a substantially younger population of stars (Hilker & Richtler, 2000) then it should be easiest to detect the different stellar populations in the vicinity of the subgiant branch, where the isochrones are well separated.

Preliminary results from new AAT 2dF observations for a sample of 900 stars redwards of the m.s., obtained in March 2002, show that faint red radial velocity members of $\omega$ Cen do indeed exist, with $17.5 < V < 18.5$ and $(B-V) > 0.8$, but the data analysis has not yet proceeded far enough to determine the metallicities of these stars and hence to trace separate isochrones. It was already clear from earlier observations that there are a number of very unusual stars lying to the red of the $\omega$ Cen main sequence, including at least one with an extreme over-abundance of Sr by a factor of about 100 (as reported by JEN at IAUXXIV, JD5, Manchester 2000).

6. Interpretation and future work

The last couple of years have seen a sudden expansion in our knowledge of abundances in faint stars in globular clusters, coming both from high resolution spectra with the new 8 – 10m class telescopes and from large samples of lower resolution spectra taken with multi-object systems. We still lack comprehensive homogeneous data for large samples of stars in all parts of the CMD for any one cluster, but it is now possible to make a few general statements.

- N over-abundances correlate with C and O depletions and some Na enhancement.
- The N abundance pattern often appears to be bi-modal, at least in the more metal-rich clusters, with comparable numbers of CN-strong and CN-weak stars.
- The abundances of most heavy elements, such as Fe and Ca, show no detectable variations within each cluster (apart from $\omega$ Cen).
- The C and N abundances needed to explain the m.s. results are approximately the same as those needed on the subgiant and giant branches.
- Clusters with similar metallicities show similar abundance anomalies.

One other key datum is the evidence that field red giants in the Galaxy show smaller abundance anomalies than similar stars in clusters (e.g. Langer et al, 1992; Charbonnel & Palacios here), which indicates that the CNO variations are probably related to the cluster environment.

All these results suggest that the CNO and Na m.s. abundance variations within clusters must be something to do with their formation and early evolution. They are apparently not due to internal nucleosynthesis and mixing.
within the cluster stars themselves (although such effects also certainly occur on the giant branch), nor can they be readily explained as a truly primordial phenomenon (e.g. if clusters formed from the collisions of separate gas clouds), since no variations are seen in Fe and Ca.

The similarity of the CNO and Na abundance patterns on the main sequence, lower and upper giant branches indicates that the abundance variations are inherent in the stars, involving at least the outer 30% of their mass. Any transient effects of a small amount of surface pollution would be wiped out when the stars leave the m.s. and develop fully convective envelopes at the base of the red giant branch.

The simplest explanation is that there was some sort of self-enrichment process within each cluster. Whether this involved mechanisms of pollution, accretion, mass exchange, binary star mergers or multiple generations of stars is not yet clear. Some or all of these processes may well have gone on during the first few times $10^8$ years of the lives of the clusters, which being < 5% of their current age would be very hard to detect in the CMDs today.

The observations imply that we are seeing the products of CNO-processed material in m.s. stars in many clusters. The most popular hypothesis for the origin of this material is that it has come from intermediate-mass stars, with masses in the range from say 2 to 5 $M_\odot$, which do produce material with the appropriate composition (e.g. Cottrell & Da Costa, 1981; d’Antona, Gratton & Chieffi, 1983). However, it is difficult to see how such material could be so efficiently accreted, or why stars seem to accrete either a large amount of material (more than 0.3 $M_\odot$) or almost none at all. Thoul et al. (2002; also poster at this conference) have revisited this problem and find that sufficiently large amounts of gas can be accreted, at least in massive concentrated clusters. Alternatively, perhaps the answer lies in the pre-supernovae stage for more massive stars, i.e. in stellar winds prior to the Wolf-Rayet phase (R. Rood, private comm.), or even in supernovae themselves, if the ejecta sometimes consist of only the outer layers where CNO has been produced but not the heavier elements, as invoked to explain the abundance patterns recently observed in some extremely metal-poor stars (e.g. Norris et al, 2002). Or, it may be that binary stars, now being recognised for their major effects in the dynamical evolution of clusters, may also be the keys to understanding the abundance anomalies. We need proper models of the early lives of globular clusters, including the star formation process and the full effects of gas flows and binary star interactions.

References

Bell, R.A. and Gustafsson, B. 1978, A&AS 34 229
Boesgaard, A.M., Deliyannis, C.P., Stephens, A. & Lambert, D.L. 1998, ApJ 493 206
Bonifacio, P. et al. 2002, A&A 390 91
Briley, M.M., Bell, R.A., Hoban, S. & Dickens, R.J. 1990, ApJ 359 307
Briley, M.M., Smith, V.V., Suntzeff, N.B., Lambert, D.L., Bell, R.A. & Hesser, J.E. 1996, Nature 383 604
Briley, M. and Cohen, J. 2001, AJ 122 242
Cannon R.D., Croke, B.F.W., Bell, R.A., Hesser, J.E. & Stathakis, R.A. 1998, MNRAS 298 601
Cannon R.D., Croke, B.F.W., Da Costa, G.S. & Norris, J.E. 2002, in “ω Cen: A Unique Window into Astrophysics”, eds. van Leeuwen, F., Hughes, J. & Piotto, G., ASP Conf. Ser. 265 119
Charbonnel, C. & Palacios, A. 2002, this conference
Cohen, J., Briley, M. & Stetson, P. 2002, AJ 123 2525
Cottrell, P. and Da Costa, G. 1981, ApJ 245 L79
d’Antona, F., Gratton, R. & Chieffi, A. 1983, Mem Soc Ast Ital 54 175
Freeman, K.C. & Norris, J.E. 1981, ARAA 19 319
Gratton et al. 2001, A&A 369 87
Gratton, R. 2002, this conference
Gustafsson, B., Bell, R.A., Eriksson, K & Nordlund, A. 1975, A&A 42 407
Harbeck, D., Grebel, E.K. & Smith, G.H. 2002, ESO Messenger 108, 26
Hesser, J.E. 1978, ApJ 223 L117
Hilker, M. & Richtler, T. 2000, A&A 362 895
Kraft, R.P. 1994, PASP 106 553
Langer, G. 1985, PASP 97 382
Langer, G.E., Kraft, R.P., Carbon, D.F., Friel, E. & Oke, J.B. 1986, PASP 98 473
Langer, G., Suntzeff, N.B. & Kraft, R.P. 1992, PASP 104 523
Lee et al. 1999, Nature 402 55
Lewis, I.J. et al. 2002, MNRAS 333 279
Norris, J.E. & Freeman, K.C. 1979, ApJ 230 L179
Norris, J.E., Cottrell, P.L., Freeman, K.C. & Da Costa, G.S. 1981, ApJ 244 205
Norris, J.E., Ryan, S.G., Beers, T.C., Aoki, W. & Ando, H. 2002, ApJ 569 107
Pancino, E., Ferraro, F.R., Bellazzini, M., Piotto, G. & Zoccali, M. 2000, ApJ 534 L83
Ramirez, S. & Cohen, J. 2002, AJ 123 3277
Smith, G.H. & Norris, J.E. 1983, ApJ 264 215
Thoul, A. et al. 2002, A&A 383 491; also this conference
van Leeuwen, F., Hughes, J. & Piotto, G. 2002, “ω Cen: A Unique Window into Astrophysics”, ASP Conf. Ser. 265