M22: a [Fe/H] abundance range revealed*

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with

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(* the revised version of a paper describing these results has been submitted to ApJ; we await confirmation of acceptance. Likely to be posted to arXiv before the end of September 2009)

- We have known for more than 30 years that *stars in globular clusters exhibit star-to-star abundance variations* in C, N, O and Na, Al, Mg with C↓ N↑ O↓ going with Na↑ Al↑ and Mg ↓. This is now known as the oxygen-sodium anti-correlation. It seems to be all pervasive in globular clusters - it’s found in all clusters studied.

- These anomalies are seen on the main sequence in at least some clusters, suggesting strongly that they are the result of process(es) occurring at the time of cluster formation. The process(es) are apparently intrinsic to globular clusters since the effects are not observed among field halo stars.

- Some clusters also show evidence for ‘double’ or ‘triple’ main sequences. These are best explained, at least from an observational point-of-view, by postulating 2 (or 3) populations with substantially different *Helium* abundances.

- *But* despite 30+ years of more and more detailed observations, we still don't have a clear and consistent understanding of how these abundance anomalies are generated. It might involve AGB stars or rotating massive stars, or both.

- However, whatever the mechanism, it has to take note of the fact that generally *globular clusters are chemically homogeneous when it come to abundances of iron-peak elements*. In many clusters the limits on any possible internal range in [Fe/H] are quite stringent, with 3σ limits ~ 0.05 dex or less.

- Of course ω Centauri is the well known exception. Not only does it show the Na-O anti-correlation, a He range, and possibly a total C+N+O range, but it also shows a range in many other elements, Fe included. The most metal-poor stars ω Cen stars have [Fe/H] ≈ –2.0, while the most metal-rich reach ~one-third to one-half solar. The cluster stars also show a variety of [element/Fe] ratios with the nucleosynthetic products of Type II and Type Ia supernovae and of AGB stars recognizable. This stellar system has likely to have had a complex chemical history with star formation occurring over a period of perhaps 2 Gyr.

- The differences between ω Cen and other clusters have led to suggestions that ω Cen may have formed in a different way from other globular clusters: that it is in fact the *remnant nucleus of a now disrupted dwarf galaxy* and this different environment allowed additional chemical evolution processes to occur that don't occur in 'regular' globular clusters.

- So is ω Cen unique? One other situation is likely relevant - the luminous cluster M54 ($M_V \approx -10.0$, cf. –10.3 for ω Cen) lies at the centre of the Sgr dwarf spheroidal galaxy, which is currently being tidally disrupted by the Milky Way galaxy. In a few Gyr M54 will be seen as a halo globular cluster rather than the central star cluster of a dwarf galaxy. Does M54 share ω Cen's pecularities?

- The situation for M54 is complicated because the star cluster is superposed on the general Sgr 'field' population, as well as the *Sgr nucleus population*. Bellazinni et al. (2008) have shown that the Sgr nuclear population is *metal-rich* ($[Fe/H] \approx -0.4$) and distinct from M54 kinematically (as well as in abundance: $[Fe/H]_{M54} \approx -1.5$).

- Nevertheless, Bellazzini et al. (2008) have obtained Ca II triplet spectroscopy of ~700 red giants in the central field of M54/Sgr. They associate ~425 of the stars with M54 and find σ_{int}([Fe/H]) = 0.14 dex for the star cluster (observed range [Fe/H] ~ – 1.8 to – 1.1), in good agreement with previous estimates.

- Thus the *case for a [Fe/H] range in M54 is strong*, but confirmation from high dispersion spectroscopic studies, which would also allow a study of [element/Fe] ratios as a function of [Fe/H], remains to be done.

The other globular cluster that is often mentioned in the context of ω Cen-like abundance variations is M22, a cluster of bright but not outstanding luminosity ($M_V \approx -8.5$).

- Early work by Hesser, Hartwick and McClure (1977) and Norris & Freeman (1983) suggested definite similarities between M22 and ω Cen. In particular, Norris & Freeman (1983) concluded from a low resolution spectroscopic survey of ~100 M22 red giants that: "There is a direct correlation between the variation of cyanogen and that of Ca II H and K, as has been reported for ω Cen. *The range in calcium line strengths corresponds to an abundance range of Δ[Ca/H] ~ 0.3*".

Since the Norris & Freeman study, the existence of possible Ca (or Fe) abundance variations in M22 has been a controversial subject, with little consensus and lots of divergent results. The biggest complication is the existence of *differential reddening across the cluster* - most authors estimate this as ΔE(B-V) ~ 0.06 to 0.08 mag.

Some examples:

- Lehnert, Bell & Cohen (1991), based on Ca II triplet region spectra of 10 red giants: "M22... is similar to ω Cen in that it displays variations in Ca, Na and Fe abundances (Δ[Fe/H] ~ Δ[Ca/H] ~ 0.4)".

- Anthony-Twarog, Twarog & Craig (1995), based on Stromgren+Ca photometry of ~300 giants and horizontal branch stars: "no independent evidence for a range in [Fe/H]". They also find differential reddening of ΔE(B-V) ~ 0.08 mag.

- Monaco et al. (2004), based on wide-field photometry of a very large sample: "the maximum metallicity spread allowed by our data is of the order of Δ[Fe/H] ~ 0.1-0.2 dex, not much more than that allowed by the photometric errors".

- Ivans et al. (2004), based on 26 red giants with high dispersion spectra: "we have found a set of spectroscopic and chemical constraints that lead to reasonable stellar parameters and *no* variations in $[\mathrm{Fe}_{\mathrm{II}}/\mathrm{H}]$".

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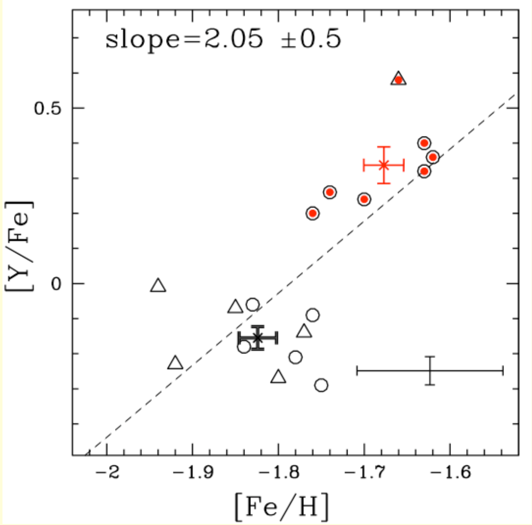
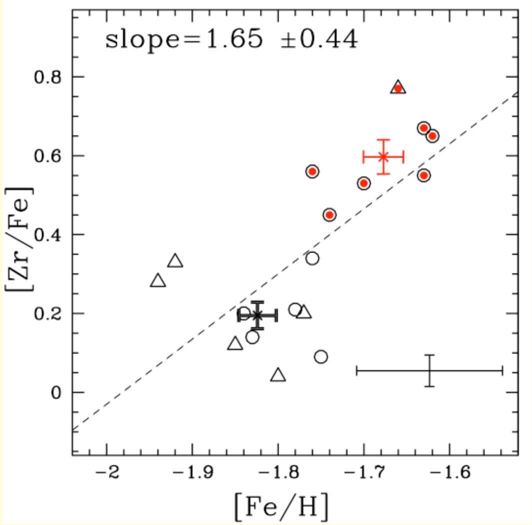
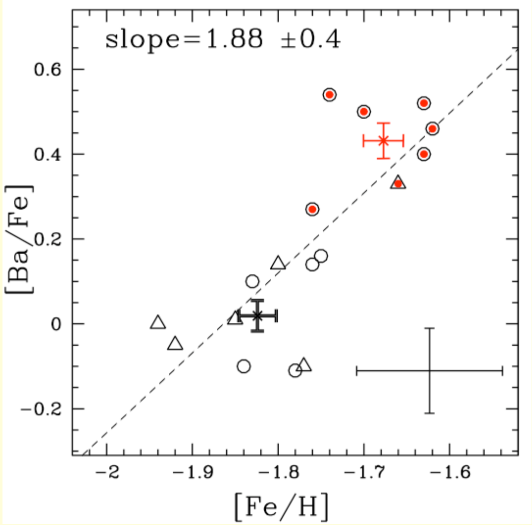
Most recently:

- Marino et al (2009, arXiv:0905.4058) have analyzed high dispersion VLT/UVES spectra for 17 M22 red giants and lower resolution GIRAFFE spectra for a further 14 stars. They identified the presence of two groups of stars whose mean abundances of the s-process elements Y, Zr, and Ba differ by ~0.6 dex. Further the s-process rich group also appears to have higher [Fe/H] and [Ca/H] abundances by 0.14 ± 0.03 and 0.25 ± 0.04 dex, respectively. More on this later...





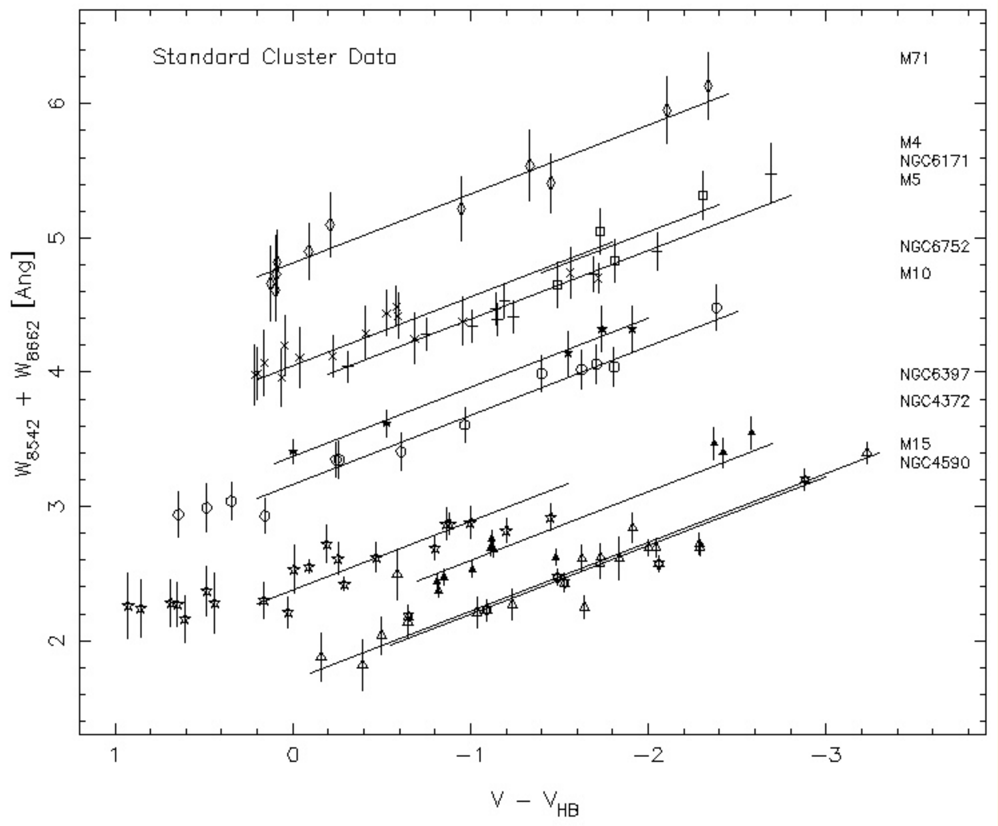


Our Program:

My collaborators and I have an ESO program to use the VLT + FORS2 to obtain spectra at the Ca II triplet of red giants in numerous Galactic globular clusters, especially those with uncertain velocities and abundances.

We have also observed a number of standard clusters with well established abundances to calibrate the observed line strengths...

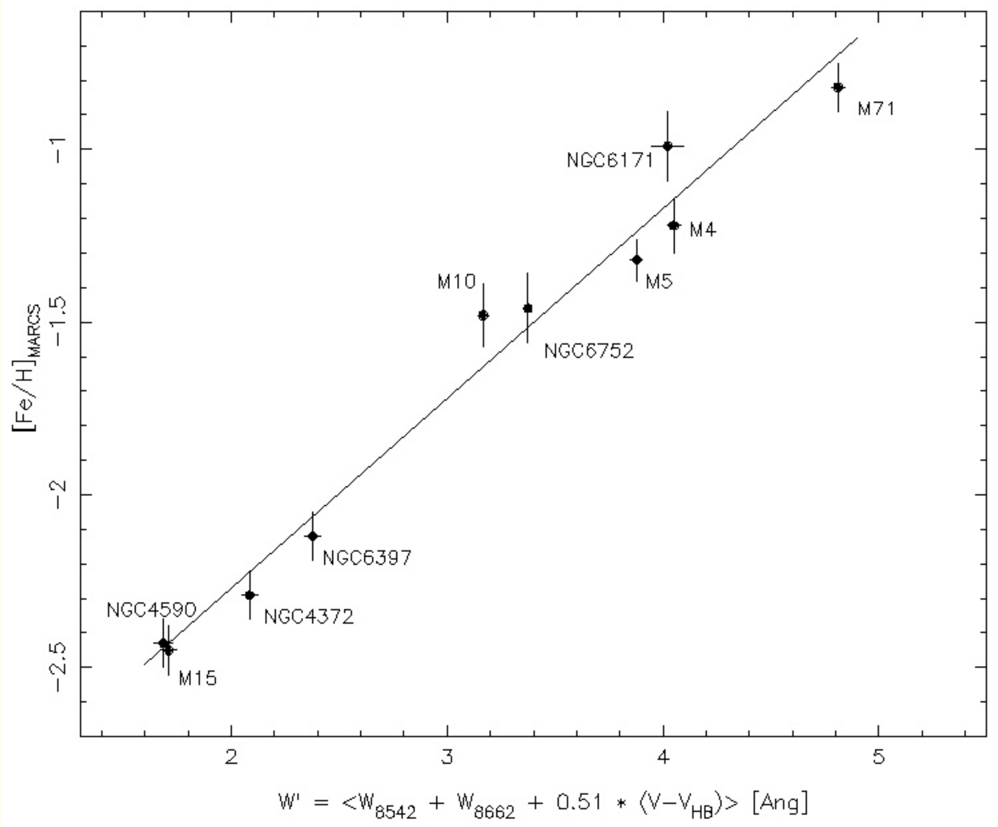
The calibration clusters are NGC 4590, M15, NGC 4372, NGC 6397, M10, NGC 6752, M5, M4, NGC 6171 and M71 all of which have well-established abundances.



Note: a) as per previous work the slope of the relation between magnitude difference from the horizontal branch $V-V_{HB}$ and $W_{8542}+W_{8662}$ is independent of abundance.

b) the NGC 6397 and M10 data suggest that the slope flattens fainter than $V-V_{HB} \sim 0$, so only stars brighter than 0.2 are included in the abundance calibration.

For the abundance calibration we adopted the Kraft & Ivans (2003) [Fe/H] scale. These authors determined [Fe/H] values by consistently analyzing high-dispersion spectra for a number of red giants in each of 16 key clusters with $-2.4 \leq$ [Fe/H] ≤ -0.7. They also considered the effects of different model atmospheres - we adopt their [Fe/H] values based on MARCS models.



The relation is linear over the entire abundance range of the calibration clusters, and the dispersion about the fitted line is consistent with the average uncertainty in the [Fe/H]$_{MARCS}$ values.

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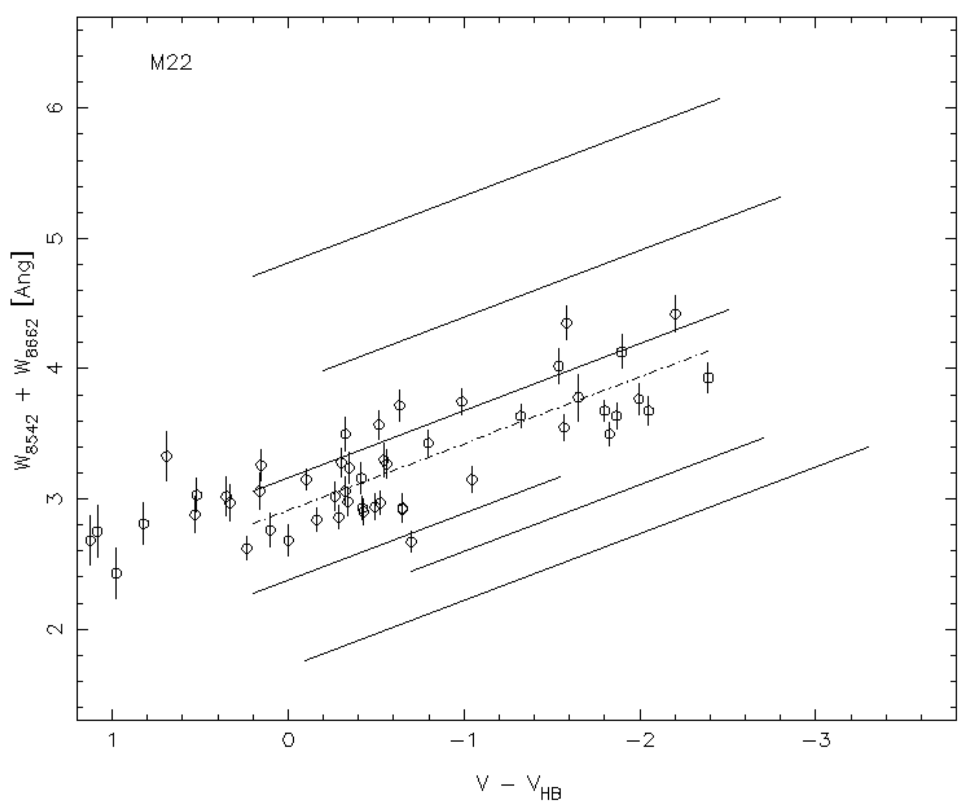
For M22 we have spectra for 55 stars, 51 have velocities consistent with cluster membership.



The fitted (dashed) line has the same slope as for the calibration clusters. Fitted only for stars brighter than $V-V_{HB} = 0.2$.

This gives an abundance for M22 of [Fe/H] = –1.77±0.10 dex, which is consistent with previous determinations.

The data show a large apparent scatter about the fitted line: the rms dispersion in $W_{8542}+W_{8662}$ at fixed $V-V_{HB}$ is 0.28Å, which is a good deal larger than the mean measurement error of 0.11Å.

None of the other clusters we have observed show such an excess over the scatter expected from the observational errors, so why is M22 different?

Could the large scatter be produced by differential reddening across the field?

Reddening variations would induce scatter in the V-V_{HB} values and thus potentially increase the scatter about the mean line.

- So we first looked at the spatial location of the stars: split the sample into 2 groups, those above the mean line (potentially more reddened than average, 19 stars) and those below the line (potentially less reddened, 22 stars).

We find that there is *no straight forward spatial separation of the two groups* over the ~7` x 7` field - if reddening variations are the explanation, then the variations must occur on scales of order ~20-30`` or less.

- The next test was to conduct Monte-Carlo trials: if we assume that in the absence of any reddening variations and observational errors the stars would all fall on the fitted line, we can ask what level of reddening variations are required to reproduce the observed scatter, given the observational errors....

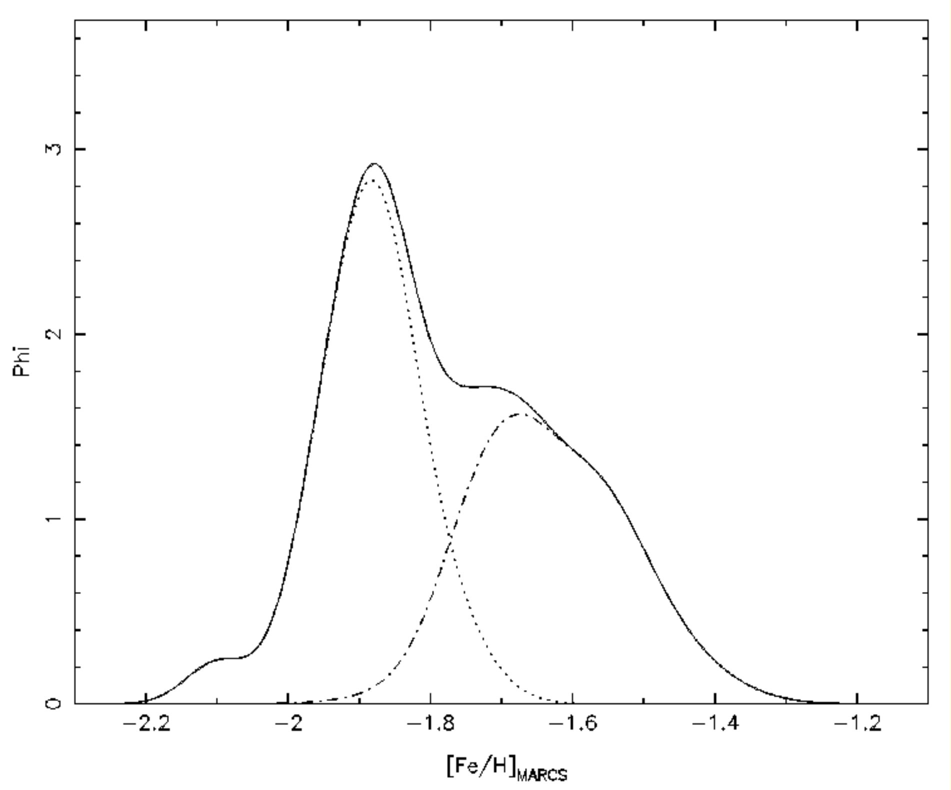
We find that to consistently reproduce the observed dispersion of 0.28Å with mean measurement errors of 0.11Å we require:

$$\sigma(E(B-V)) = 0.12 - 0.15 \text{ mag}$$

This value is *considerably larger than existing estimates,* which are that the *total range* in E(B-V) *across the entire cluster* is ~0.06 - 0.08 mag, i.e. $\sigma(E(B-V)) \sim 0.02 - 0.03$ mag.

- **We conclude therefore that there is an intrinsic spread in the W_{8542}+ W_{8662} values for the M22 stars, over and above that due to any differential reddening. This is prima facie evidence for the existence of an intrinsic abundance spread in the cluster.**

We can then use the abundance calibration to produce an abundance estimate for each individual M22 star from its $V-V_{HB}$ and $W_{8542}+W_{8662}$ values, at least for those stars with $V-V_{HB}$ values inside the calibrated range. For the present we ignore the minor effects of differential reddening: if $\sigma(E(B-V)) \approx 0.02$ mag, then through the effect on $V-V_{HB}$ it introduces $\sigma([Fe/H]) \approx 0.02$ dex, which is negligible in current context.



Shown as the solid line is a generalized histogram for the 41 individual $[Fe/H]_{MARCS}$ values made using the $[Fe/H]_{MARCS}$ errors that follow from the errors in the $W_{8542}+W_{8662}$ values. The average of these is 0.06 dex.

Shown also are the contributions of the stars below the mean line (more-metal-poor, dotted line) and of the stars above the mean line (more metal-rich, dot-dash line).

- Clearly there are *multiple components* in the abundance distribution: there is a sharp rise to a narrow peak at $[Fe/H]_{MARCS} = -1.88$ with a broad tail to higher abundances. We can characterize this abundance distribution in a number of ways...

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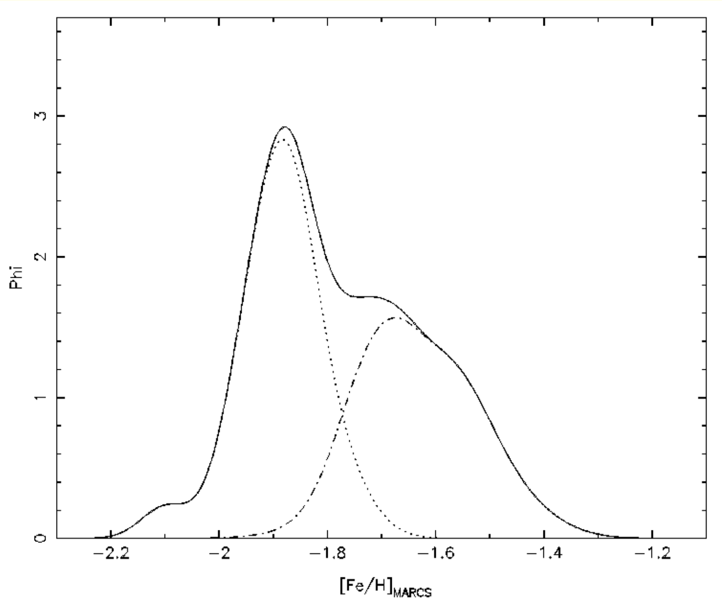
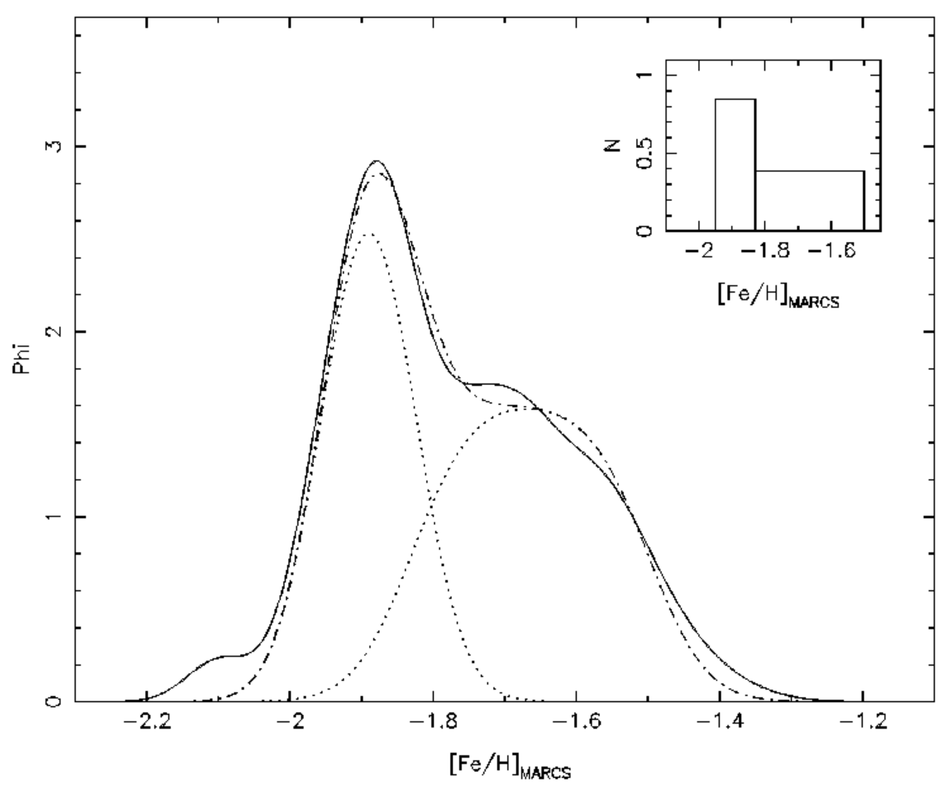


- For the whole sample, the inter-quartile range is 0.24 dex, which is close to the values suggested by Norris & Freeman (1983), Lehnert et al. (1991). It is comparable with the Marino et al (2009) results but clearly in conflict with Ivans et al (2004).
- The most metal-poor star has [Fe/H]$_{\mathrm{MARCS}}$ = –2.1 and it is 0.14±0.07 more metal-poor than the next most metal-poor star. A small third low metallicity grouping? Outlier? (Need larger sample).
- The most metal-rich star has [Fe/H]$_{\mathrm{MARCS}}$ = –1.45 (0.08 ±0.10 from next, likely just the tail of the distribution).

- For the 22 stars in the metal-poor group, the inter-quartile range is only 0.05 dex (smaller than the mean error), while for the metal-rich group, the inter-quartile range is notably larger at 0.16 dex. The median for these stars is [Fe/H]$_{\mathrm{MARCS}}$ = –1.64 dex.

Can we model the distribution...?

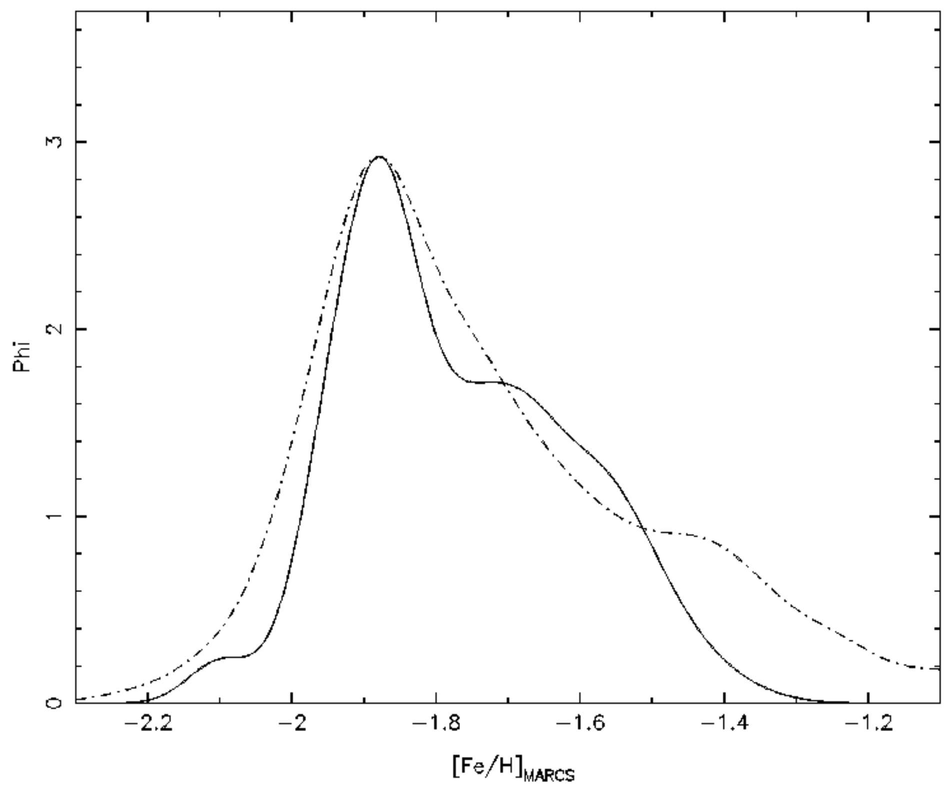


Toy model. M22 has *two* populations:

1: abundances uniformly distributed between [Fe/H] = –1.95 and –1.83 (44% of total)
2: abundances uniformly distributed between –1.83 and –1.50 (56% of total).

- Convolution with measurement errors gives acceptable representation of observations.

Inset shows input abundance distribution. Dotted lines are the two components and dot-dash line is their sum. Solid line is the observations. The model doesn't reproduce the metal-poor tail, but observationally the tail results from a single star. Note: assuming a single abundance for metal-poor group doesn't give an adequate fit. Perhaps a single abundance plus differential reddening might do it, but seems unlikely (not yet modeled).



How does M22 compare with ω Cen?

Solid line is the M22 data (41 stars) while dot-dash line is the abundance distribution for ω Cen from Norris et al (1996, ApJ, 462, 241), which is based on [Ca/H] abundances for ~500 stars.

ω Cen distribution shifted first by –0.4 (mean [Ca/Fe] for ω Cen stars) and then a further –0.09 to make the peaks coincide. Peak height then normalized to that for M22.

The ω Cen distribution is certainly broader than for M22 on the metal-rich side (recall ω Cen has stars up to [Fe/H] ≈ –0.5) but the metal-poor sides are ~similar. The 'second peak' in M22 is closer in abundance to first peak than for ω Cen, and ω Cen contains further 'peaks' at higher abundances than shown. This difference is probably not the result of the smaller size of the M22 sample. *General similarity suggests they result from the same physical process(es) but it continued longer in ω Cen. Mass effect?*

What other similarities are there between M22 and ω Cen?

- Both clusters have strong blue horizontal branches, although that of M22 isn't unusual given its relatively low mean abundance and relatively small distance from the Galactic Centre - i.e. it's a normal 'old-halo' cluster in the terminology of Zinn or Lee.

- What about orbit? ω Cen has a tightly bound retrograde orbit in which it never rises very far from the Galactic Plane. The compilation of Dinescu et al. (1999) shows that the M22's orbit is ~typical for inner halo objects. It has both similarities and differences to that of ω Cen. M22's orbit is strongly prograde, and its apo- and peri-galactocentric distances are both larger than ω Cen's, as is the maximum height above the plane. The orbital inclinations are similar.

Cluster	R_{apo}	R_p	Z_{max}	P(Myr)	ψ(deg)	Θ(kms-1)	e
ω Cen	6.3	1.2	1.0	120	17	–65 ± 10	0.68
M22	9.5	2.9	1.8	195	17	178 ± 20	0.54

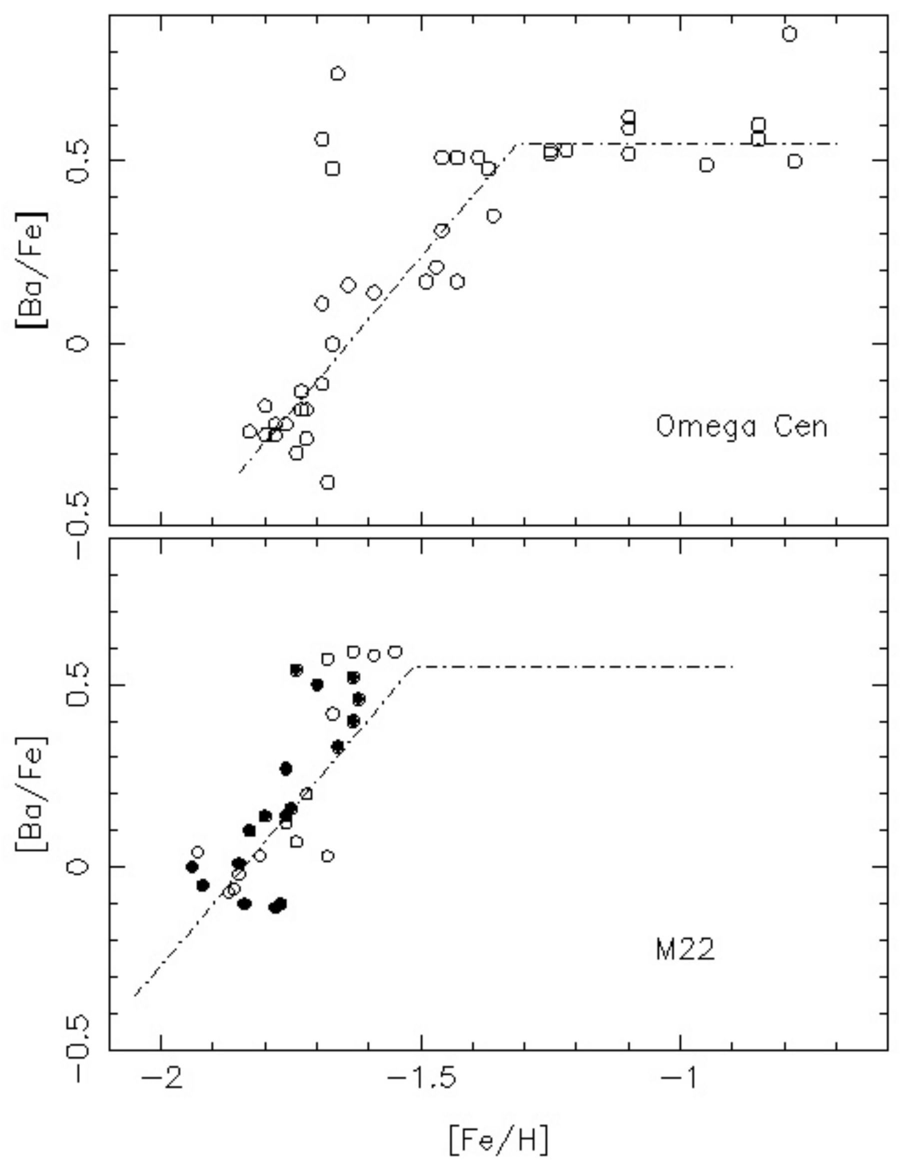
Given that Bekki & Freeman (2003) have shown that it is possible to start with a nucleated dwarf galaxy at a large galactocentric distance and end up with the nuclear remnant in an orbit resembling that of ω Cen, it seems likely that this would also be possible for M22.

Comparison with the results of Marino et al (2009, arXiv:0905.4058)

- There are three stars in common between the UVES observations and our sample. These stars have Δ[Fe/H] (Marino - us) of 0.09±0.11, 0.02±0.13 and 0.01±0.11 dex, indicating excellent agreement.

- A (two-sided) K-S test shows that the [Fe/H] abundance distribution for the 30 stars in the Marino et al (2009)[UVES + GIRAFFE] data is consistent with that from our observations - the hypothesis that both samples come from the same underlying distribution cannot be ruled out, even at 10% significance level.

- We can also use the Marino et al (2009) individual abundance ratios to extend the comparison of M22 with ω Cen...

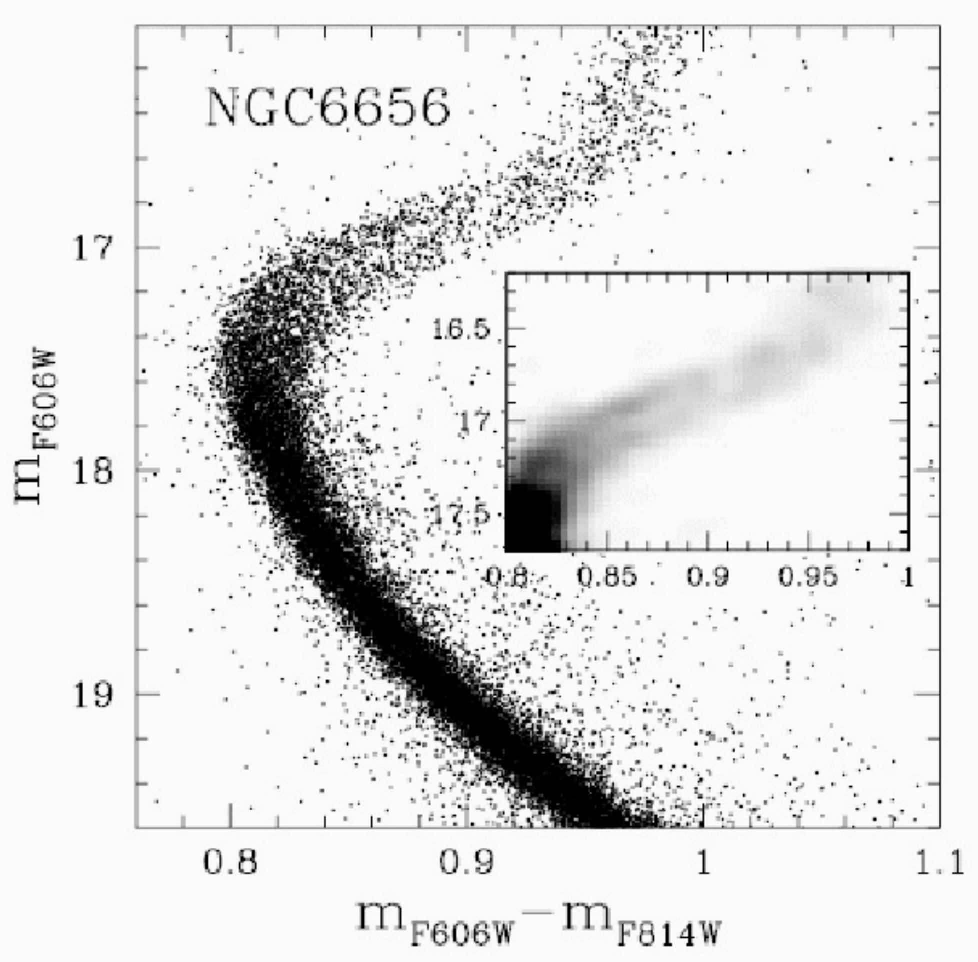


Upper panel shows [Ba/Fe] vs [Fe/H] for 40 red giants in ω Cen from Norris & Da Costa (1995). The [Ba/Fe] ratio rises with increasing [Fe/H] until [Fe/H] ≈ −1.3, after which the Ba and Fe abundances change in lock step.

Lower panel shows [Ba/Fe] versus [Fe/H] for the 30 M22 red giants from Marino et al (2009). The ω Cen relation, shifted to lower [Fe/H] by 0.2 dex, fits the M22 data.

Similar results apply for the other s-process elements Y and Nd.

Likely that similar enrichment processes went on in both stellar systems.



- M22 colour-magnitude diagram shown is from Piotto (2009, arXiv:0902.1422). These HST-based data show a broad, perhaps even bimodal, subgiant branch.

It is tempting to conclude this is related to the observed abundance spread, with the lower branch corresponding to the more metal-rich population, and a negligible age difference. The difference in F606W mag is compatible with our mean abundance difference of ~0.23 dex, and the population ratios from the CMD (38±5% 'metal-poor', 62±5% 'metal-rich') are also consistent with our results (44% metal-poor, 56% metal-rich).

Note though that there doesn't seem to be much evidence for a separate 'blue' (He-rich?) main sequence as seen in ω Cen.

Conclusions

- Spectra of a sample of ~50 members of the globular cluster M22 at the Ca II triplet has shown that there is an *intrinsic [Fe/H] abundance dispersion present in the cluster.*

- The abundance distribution rises sharply to a distinct peak at [Fe/H] ≈ –1.9 with a broad tail to [Fe/H] ≈ –1.5. It is probable that at least two components are needed to describe the distribution.

- M22 then joins ω Cen and M54 as the only clusters in which such [Fe/H] ranges are known. M54 is currently the central star cluster of the Sgr dSph and ω Cen is frequently postulated as being the remnant nucleus of a disrupted dwarf galaxy. *It therefore seems logical to conclude that M22 may also be the remnant nucleus/nuclear star cluster of a disrupted dwarf galaxy.*

- A comparison of the variation with [Fe/H] of s-process abundances between M22 and ω Cen shows strong similarities, consistent with the idea that the same enrichment process(es) occurred in both systems, though it apparently terminated earlier in M22.