Chemical Abundance Inhomogeneities in Globular Cluster Stars

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ABSTRACT

It is now clear that abundance variations from star-to-star among the light elements, particularly C, N, O, Na and Al, are ubiquitous within galactic globular clusters; they appear seen whenever data of high quality is obtained for a sufficiently large sample of stars within such a cluster. The correlations and anti-correlations among these elements and the range of variation of each element appear to be independent of stellar evolutionary state, with the exception that enhanced depletion of C and of O is sometimes seen just at the RGB tip. While the latter behavior is almost certainly due to internal production and mixing, the internal mixing hypothesis can now be ruled out for producing the bulk of the variations seen. We focus on the implications of our new data for any explanation invoking primordial variations in the proto-cluster or accretion of polluted material from a neighboring AGB star.

Over the past two decades the upper giant branches of the nearer GCs have been well studied with 4-m class telescopes by, among others, the Lick-Texas group (see Sneden et al 2004 and references therein) or the Padua group (Gratton and his collaborators, see, e.g. Carretta & Gratton 1997) (see also the early review of some of the issues to be discussed here by Kraft 1994 and the recent review of Gratton, Sneden & Carretta 2004). Recently 10-m class telescopes coupled with efficient spectrographs have enabled us to explore detailed abundance ratios and chemical history ever deeper in the stellar luminosity function in galactic globular clusters (GCs). We can now reach with considerable precision the RGB in *all* galactic GCs (see, for example, the study of NGC 7492, at a distance of 26 kpc, by Cohen & Melendez 2005b). For the nearer GCs, abundance analyses for the brightest main sequence stars in the nearest GCs, and for the subgiant branch for those slightly more distant, are now feasible.

The chemical analyses within the past 5 years in which the author has been involved include the GCs NGC 6528 (Carretta et al 2001), NGC 6533, M71, M5 (Ramírez & Cohen 2003), M3, M13 (Cohen & Melendez 2005a and reference therein) and shortly M15 and M92 as well as NGC 7492 (Cohen & Melendez 2005b) and Pal 12 (Cohen 2004), all observed with HIRES (Vogt et al. 1994) at Keck. Our approach is to study stars over the full range of luminosity from the RGB tip to the faintest possible that can be reached in 2 to 4 hours of integration. The large program carried out with UVES at the VLT described in Gratton et al (2001) concentrate on comparing subgiants with a small number of main sequence stars in the nearest southern clusters.

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Viewing in totality the collective effort of these and other groups, we find that star-to-star abundance variations from star-to-star among the light elements, particularly C, N, O, Na and Al, are ubiquitous. They are seen whenever data of sufficient quality is obtained for a sufficiently large sample of stars within a galactic globular cluster. Our most recent Na-O anti-correlation, for M13, with a sample of 25 stars reaching almost to the main sequence turnoff can be seen in Fig. 16 of Cohen & Melendez (2005a), not shown here due to lack of space.

The correlations and anti-correlations among these elements for stars in GCs and the range of variation of each element resemble those of proton-burning. They appear to be independent of stellar evolutionary state, with the exception that enhanced depletion of C and of O is sometimes seen just at the RGB tip. This extra depletion of O just near the RGB tip is seen in our M13 data shown (see also Sneden et al 2004). Metal poor halo field stars, however, show no evidence for O burning (Gratton et al 2000) or Na enhancement. The variations seen in the field stars are much closer to those predicted by classical stellar evolution that those seen in the GC stars.

At the same time, the abundance ratios among the elements heavier than Al, at least through the Fe peak, do not show any detectable variation in any known GC (except, of course, ω Cen). The rock steady abundances for these elements requires explanation as well, and places important constraints on the formation mechanisms of GCs.

Interesting as this is, we are still plagued, when observing at high dispersion, with small samples, at least until FLAMES came into use. Small samples trying to discern small variations is not the ideal combination.

My approach to this issue has been to use the molecular bands of CH, CN and now NH to study the star-to-star abundance variations of C and of N. Since these bands are strong enough to be observed at moderate resolution, I can use the multiplexing capability of the Low Resolution Imaging Spectrograph at Keck (Oke et al 1995) to build up large samples. This effort is being undertaken jointly with Michael Briley of the University of Wisconsin at Oshkosh and with Peter Stetson of the National Research Council, Victoria, Canada.

We have now analyzed large samples of low luminosity stars (subgaints or main sequence turnoff region stars) in each of four GCs spanning a wide range in metallicity. In each cluster we have a sample of $\sim$70 stars. Our most recent work, a study of M15, is being written up for publication. Our analyses of M71, M5 and M13 are already published (see Cohen, Briley & Stetson 2002, Briley, Cohen & Stetson 2002 and 2004b, and references therein). We derive C/Fe from the CH band, and N/Fe from the CN band. For M15 we must use the NH band at 3360 Å; the CN bands are too weak. This has the advantage of achieving a N/H ratio which is to first order independent of the C abundance, which would not hold were CN to be used for this purpose.

Fig. 10 from our study of a large sample of stars in M5 (Cohen, Briley & Stetson 2002) (not reproduced here due to limits of length) is typical of the GCs studied thus far in such detail. It shows a strong anti-correlation between C and N abundances, i.e. conversion of C into N, with strong-to-star variations in derived C and N abundances seen at all luminosities probed. (This
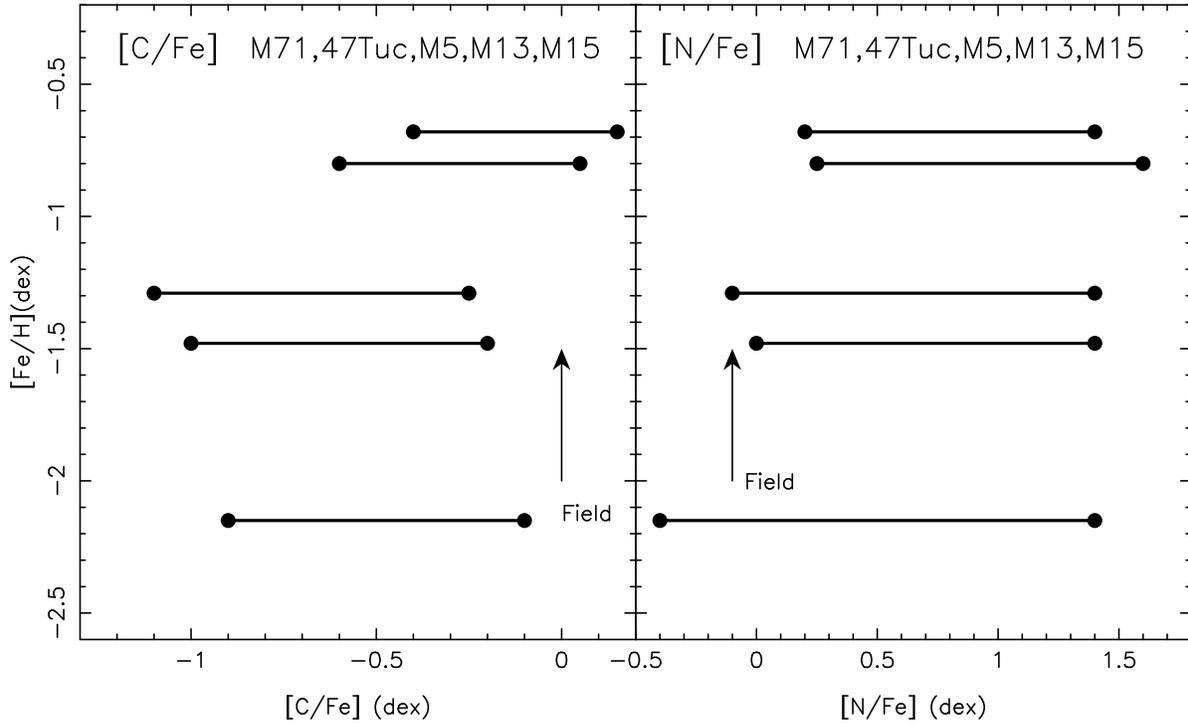
Fig. 1.— The range of [C/Fe] (left panel) and [N/Fe] (right panel) is shown as a function of metallicity ([Fe/H]) for the globular clusters from our work on M71, M5, M13, and M15 as well as for 47 Tuc (from Briley et al 2004a). Large samples of stars, mostly subgiants, were used in each case. Each GC is represented by a horizontal line. The characteristic field star ratio, from Carretta, Gratton & Sneden (2000) for C and from Henry, Edmunds & Koppen (2000) for N, are indicated by vertical arrows in each panel.

sample contains mostly stars at the base of the RGB and just below the main sequence turnoff, with V $\sim$ 16.5 to 19 mag, where the turnoff of M5 is at about 18.2 mag.) We also find ON burning is required to reproduce the most extreme N enhancements, which are very large. In our paper, we commented that external pollution from a nearby AGB star, presumably a binary companion, perhaps can match the star-to-star abundance patterns seen in GCs, but does not seem capable of producing the highly organized abundance variations as such an "external" mechanism is stochastic in nature. Furthermore, the amount of "polluted" mass that needs to be accreted becomes a significant fraction of the total mass of the low luminosity star. The popular AGB companion hypothesis is beginning to crumble at this point.

Combining all our data with the study of 47 Tuc by Briley et al (2004a), we determine roughly the range in $[X/\text{Fe}]$, where X is either C or N, in each GC. The results are shown in Fig. 1; the vertical arrows indicate the mean location of metal poor field stars. Note that the field star mean coincides roughly with the GC high end of the range for C and with the low end of the GC range for N. These GCs span a range in metallicity of a factor of $\sim$40. Yet we find that this range is approximately constant for both C and for N. Thus the additional material is not from some primary process which dumps a fixed amount of N into the GC gas. Instead it behaves like a secondary process, increasing as $[\text{Fe/H}]$ increases. Since the production of C and N in AGB stars is to first order a primary process, this strongly suggests that ejecta from AGB stars do not cause the star-to-star variation in the abundance of these elements in GCs. This leaves some kind of variation imprinted in the proto-cluster before the present generation of stars we now observe were formed as the only viable scenario. Furthermore the source of this cannot have been some previous generation of AGB stars, unless mass loss rates vary proportionately to metallicity. While it is believed that they do increase with metallicity, the factor generally discussed is far smaller than the factor of 40 range in our GC sample.

So after more than 20 years of searching for an answer, we have much better data on the nature of star-to-star variations in the abundances of the light elements in GCs, but still no definitive understanding of the physical mechanism(s) responsible, nor of why metal poor field halo stars do not show these phenomena.

REFERENCES

Briley, M. M., Cohen, J. G. & Stetson, P. B., Ap.J.L., **579**, L17 (2002)

Briley, M. M., Harbeck, D., Smith G. H. & Grebel, E. K., AJ, **127**, 1588 (2004a)

Briley, M. M., Cohen, J. G. & Stetson, P. B., AJ, **127**, 1579 (2004b)

Carretta, E. & Gratton, R. G., A&AS, **121**, 95 (1997)

Carretta, E., Cohen, J. G., Gratton, R. G. & Behr, B. B., AJ, **122**, 1469 (2001)

Carretta, E., Gratton, R. & Sneden, C., A& A, **356**, 238 (2000)

Cohen, J. G., AJ, **127**, 1545 (2004)

Cohen, J. G., Gratton, R. G., Behr, B. B. & Carretta, E., ApJ, **523**, 739 (1999)

Cohen, J. G., Behr, B. B. & Briley, M. M., AJ, **122**, 1420 (2001)

Cohen, J. G., Briley, M. M. & Stetson, P. B., AJ, **123**, 2525 (2002)

Cohen, J. G. & Melendez, J., AJ (in press) (2005a)

Cohen, J. G. & Melendez, J., AJ (in press) (2005b)

Gratton, R. G., Sneden, C., Carretta, E. & Bragaglia, A., A&A, **354**, 169 (2000)

Gratton, R. G., et al, A&A, **369**, 87 (2001)

Gratton, R. G., Sneden, C. & Carretta, E., Ann. Review Astron. & Astrophys, **42**, 385 (2004)

Henry, R.C.B., Edmunds, M.G. & Koppen, J., ApJ, **541**, 660 (2000)

Kraft, R. P., 1994, PASP, **106**, 553 (1994)

Oke, J. B., et al., PASP, **107**, 375 (1995)

Ramírez, S. V. & Cohen, J. G., AJ, **123**, 3277 (2002)

Ramírez, S. V. & Cohen, J. G., AJ, **125**, 224 (2003)

Sneden, C., Kraft, R. P., Guhathakurta, P., Peterson, R. C. & Fulbright, J. P., AJ, **127**, 2162 (2004)

Vogt, S. E. et al, SPIE, **2198**, 362 (1994)