Abundances in Globular Cluster Stars: What is the Relation with Dwarf Galaxies?

Raffaele Gratton
INAF – Osservatorio Astronomico di Padova, Italy

In the last few years increasing evidence has accumulated for some chemical evolution within globular clusters. The evidence is much clearer for the most massive clusters. Many authors have proposed that (at least the most massive) globular clusters may be closely related to the nuclei of dwarf galaxies. I review recent results on the chemical inhomogeneities in globular clusters and discuss the perspectives opened up by these results.

Globular clusters and dwarf galaxies

The distinction between globular clusters (GCs) and dwarf galaxies is based mainly on their structural properties. A useful recent discussion can be found in Dabringhausen et al. (2008). GCs and Ultra-Compact Dwarf (UCD) galaxies seem to define a unique sequence in the mass versus central density plane, suggesting a similar formation scenario, while Dwarf Spheroidals (dSphs) are clearly separated. Although GCs and UCD galaxies seem to form a continuum, they differ significantly in their two-body relaxation time. For GCs this is shorter than a Hubble time, while for UCDs it is longer. As a consequence, GCs are relaxed objects, while UCDs are not. This has important implications for their mass-to-light ratio. There is scarce evidence of dark matter in both GCs and UCD galaxies, in agreement with expectations based on their size. However GCs have a lower mass-to-light ratio, probably because of dynamical evolution (since they are relaxed objects): in fact, due to energy equipartition and hence mass segregation, they selectively lose faint low mass stars. While these differences are on the whole clear, classification of borderline objects, like ω Centauri, is not obvious. However, the presence of a continuum of properties may be used to improve our understanding of the mechanisms that lead to the formation of GCs.

Both GCs and dwarf galaxies are known to lose stars to the general field, as clearly shown by the presence of tidal tails. Two good examples are provided by the dSph galaxy Sagittarius, whose tail can be followed around the Milky Way, along an entire great circle (Belokurov et al., 2006) and by the GC Pal 5 (Odenkirchen et al., 2001). This phenomenon of stellar loss has two consequences: (i) a (perhaps small) fraction of stars in the Galactic halo should originate in these environments; and (ii) the observed populations of GCs and dSphs represent the surviving components of wider original populations. However the average properties of the original populations might be quite different from those of the survivors. This distinction has important implications for the so-called missing satellites problem.

Since dSphs and GCs may contribute to the halo population, it is interesting to compare their chemical composition to that of field halo stars. Early results for dSphs were very discouraging (see the discussion in Geisler et al., 2007). However, very recently Kirby et al. (2008) found that the metallicity distribution of the most metal-poor field stars agrees reasonably well with that of stars in ultra-faint dSphs. For GCs, we may compare the well-known bimodal distribution of abundances of GCs with the results obtained by Ivezic et al. (2008) for a large number of halo and thick disc stars observed in the Sloan Digital Sky Survey (SDSS). They found that the metallicity distribution function of stars out of the Galactic plane can be described by the sum of a moderately metal-poor disc and of a more metal-poor halo. These two components may well be traced in the GC metallicity distribution function. The disc GCs correspond to the moderately metal-poor disc at $|z| = 0.8$–1.2 kpc while the halo ones correspond to the metal-poor halo at $|z| = 5$–7 kpc. The specific frequency of GCs is however much larger in the halo component than in the disc one.

An interesting property of dwarf galaxies is that their (mean) metallicity depends on luminosity: Kirby et al. (2008) provided a good version of this relation for the case of dSphs. This relation fits with the concept that dSphs make their own metals. On the other hand, the metallicity of GCs is fairly independent of luminosity (and mass), suggesting that they inherited the metallicity of the medium in which they formed. Interestingly, at a given luminosity, the dSph metallicity is a lower envelope to the GC metallicities. This effect has potential implications for the connection between GCs and dSphs, and merits further examination.

Geisler et al. (2007) made a fairly extensive comparison between the element-to-element abundance ratios observed in dSphs and field halo stars. They found that dSph stars have very peculiar abundances of O, α-elements, Na (which are all underabundant) and s-process elements (which are overabundant). These abundances are all indicators of very slow star formation, as expected in these low density environments. Differences from typical halo stars imply that only a very minor fraction of the halo stars may have come from the present dSphs. There are, however, a few halo field stars with compositions similar to that of stars in the Magellanic Clouds and in the most massive dSphs (such as Sagittarius: Mottini & Wallerstein, 2008; Sbordone et al., 2006; Letarte et al., 2006).

Figure 1 compares the abundances of GC stars with those of field stars from the work by Carretta et al. presented in the last part of this review. In general, GCs have a composition similar to that of the Galactic halo, save for the O-Na anticorrelation (see last section). The P (likely primordial, see below) population in GCs has a composition virtually identical to that of field stars.

Finally, we may compare the age–metallicity relation for Milky Way GCs (Rosenberg et al., 1999; De Angeli et al., 2005) with that for dSphs like Sagittarius (Mottini & Wallerstein, 2008) and Sculptor (Tolstoy et al., 2003). The differences are obvious: the metallicity rose very fast in the Milky Way, and reached a solar value within 2 Gyrs; it increased much more slowly in the dSphs, being still below one tenth solar after several Gyrs.

Are GCs the nuclei of mostly dissolved dwarf galaxies?

Most GCs are extremely homogeneous in terms of the Fe-peak elements, with star-to-star variations no larger than 10 % (Gratton et al., 2005; Carretta et al.,

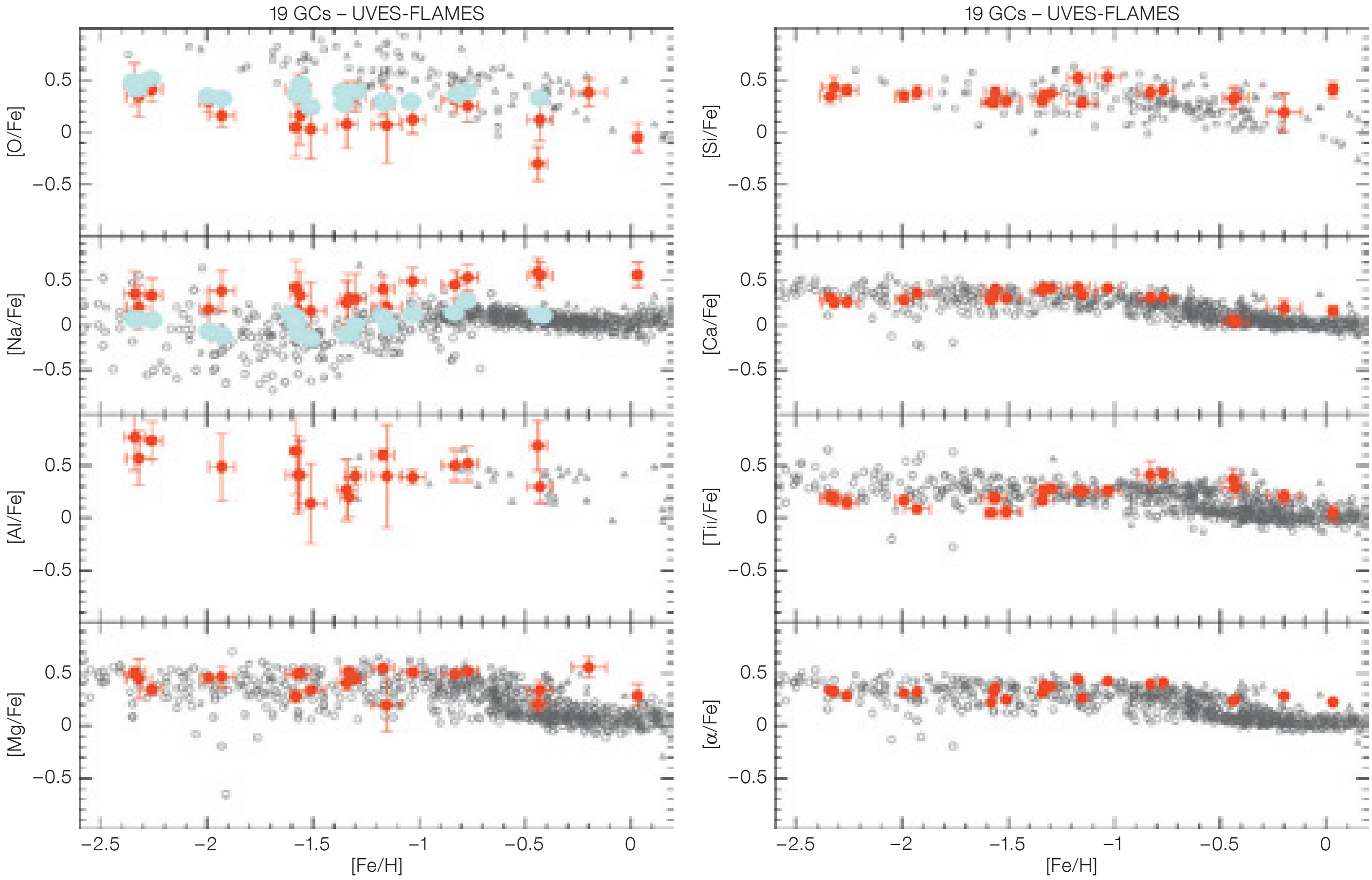

Figure 1. Abundances as a function of the metallicity [Fe/H] for GC stars (Carretta et al.: red-filled symbols) compared with those of field halo stars from the compilation by Venn et al. (2004), as grey circles. Only O, Na and other α-elements are shown. For O and Na, abundances of the primordial population in GCs are also indicated, as cyan-filled symbols.

2007a). On the other hand, significant and occasionally large abundance variations in elements produced by SNe have been found. Given the large kinetic energy injected into the interstellar medium by SNe, deep potential wells and thus large masses are required to explain similar abundance spreads. This conclusion leads directly to the idea that at least some of the GCs were nuclei of presently dissolved dwarf galaxies.

M54, which is located at the core of the disrupted dSph in Sagittarius (Sgr), plays a fundamental role in this respect. Very recently, Bellazzini et al. (2008) published an interesting study of M54 and its environment. They measured radial velocities and estimated abundances for about 1200 stars. Their data allowed the sample to be cleaned of foreground Milky Way interlopers, and M54 stars to be separated from the Sgr ones. The most important result is that the Sgr galaxy has a nucleus (Sgr N), even without considering M54. The centres of Sgr N and M54 coincide to within 2 arcsec (0.2 pc) and 0.8 km/s in radial velocity. Both M54 ([Fe/H] ~ −1.6) and Sgr N ([Fe/H] ~ −0.6) have a spread in metallicity. Bellazzini et al. then considered the stellar distribution on the sky and the radial velocity dispersion for the two populations. They found that M54 and Sgr N stars have different runs of velocity dispersion with radius: for M54 the velocity dispersion decreases with radius in a "mass follows light" fashion (Gilmore et al., 2007) like typical GCs; Sgr N however has the same flat velocity dispersion as the inner regions of Sgr, likely influenced by dark matter and in agreement with Navarro-Frenk-White models. Some evidence was also found for extratidal stars from M54 in the field of Sgr, although this might rather be due to contamination by Sgr stars in the outer radial bins. Finally Bellazzini et al. considered the birthplace of M54, simulating its possible past orbit within Sgr. They concluded that M54 might have formed as far as several kpc from the nucleus of Sgr, and then have sunk towards the centre of the galaxy due to dynamical friction. The other Sgr GCs are too small and too far from the centre of Sgr for dynamical friction to have been important.

These results can be used to speculate on the origin of the nuclei of dwarf galaxies. Bellazzini et al. concluded that the simultaneous presence of M54 and Sgr N suggests that the nuclei of dwarf galaxies may form both from infall of GC(s) to the centre of the galaxy, and from *in situ* formation by the accumulation of gas at the centre of the potential well and its subsequent conversion into a stellar overdensity.

Multiple populations in GCs

M54 is unique because we can, unlike the nuclei of other galaxies, resolve the individual stars in its nucleus. However, multiple populations are seen in other GCs. The most famous example is ω Centauri. While the wide red giant branch (RGB) and abundance spread of this GC have been known since the 1960s, the first extensive study of the abundance distribution was conducted by Suntzeff & Kraft (1996), who found clear indications for a huge mass loss. As more sophisticated instrumentation became available, a clear separation of the RGB into various sequences was found by Ferraro et al. (2004), showing that the distribution of stars with metallicity is not continuous, but that it shows evidence of various episodes of star formation; notably, Pancino et al. (2002) observed a metal-rich population, with [Fe/H] ~ −0.6.

The composition of rather large samples of RGB stars in ω Centauri has been studied by Norris & Da Costa (1995) and Smith et al. (2000). The metal-rich population is very rich in s-process elements, requiring prolonged star formation. The age-metallicity relation from the subgiant branch (SGB) and turn-off stars has been obtained by Stanford et al. (2006), using 4 m ground-based photometry and spectroscopy, and showing a spread of several Gyrs. Progress in instrumentation (HST/ACS photometry, spectroscopy with 8 m telescopes) has allowed multiple SGB sequences to be distinguished (Villanova et al., 2007) and demonstrated that the age-metallicity relation is not monotonic, with old metal-rich and younger metal-poor sequences. Element-to-element abundance trends among SGB stars were found to be similar to those among RGB stars.

However, the most exciting results concern the splitting of the Main Sequence (MS) described by Bedin et al. (2004). ω Centauri has at least two MSs: a bluer and a redder. The bluer one contains a quarter of the stars, which fits with the fraction of stars that are more metal-rich; the redder contains three quarters of the stars and fits with the more metal-poor fraction (Suntzeff & Kraft, 1996). Piotto et al. (2005) confirmed that the bluest MS is more metal-rich ([Fe/H] ~ −1.2) than the redder one ([Fe/H] ~ −1.6), but this implies a higher He-content (Y ~ 0.4 rather than 0.25)! Comparison of the populations in the various sequences suggests that the He-rich MS is connected to the extreme Blue Horizontal Branch (BHB).

Multiple populations are also observed in other GCs. NGC 2808 is one of the most luminous GCs. Carretta et al. (2006) found a large spread in the O-Na anticorrelation, but no spread in Fe-peak abundances. The horizontal branch (HB) is discontinuous, with a well-populated Red Horizontal Branch (RHB), and an extended BHB, but few RR Lyrae stars. Piotto et al. (2007) found that there are three MSs; they can be explained by different He-contents (Y = 0.25, 0.30 and 0.37). There is no splitting of the SGB and of the RGB, indicating similar age and metallicity for the three populations. The distribution of stars amongst these populations suggests that the RHB is connected to the He-poor population, and the extended BHB to the He-rich one.

NGC 1851 is somewhat less massive. The HB is discontinuous, with a well-populated RHB, and an extended BHB, but few RR Lyraes. Milone et al. (2008) found that there are two SGBs; the magnitude difference corresponds to about 1 Gyr, but can also be explained by a spread in the abundances of CNO elements. On the other hand, there is no splitting of the upper RGB or the MS (implying a similar metallicity and He content for the two sequences). Both the population and the central concentration suggest that the RHB is connected to the younger SGB, and the extended BHB to the older SGB. The chemical composition of NGC 1851 has been studied by Yong & Grundahl (2007), who found no variation in Fe, an extended Na-O anticorrelation and variations of Ba and La correlated with Na; this latter finding suggests some contribution by thermally pulsing asymptotic giant branch (AGB) stars.

Looking at other massive clusters, wide RGBs have also been found in massive clusters in M31 (Meylan et al., 2001; Fuentes-Carrera et al., 2008). In the Milky Way, NGC 6388 and NGC 6441 are difficult to study due to differential reddening, but their HB is discontinuous, which again suggests multiple populations. However, detailed studies of 47 Tuc do not show obvious multiple populations.

The O-Na anticorrelation

Discovered in the 1970s, the O-Na anticorrelation is probably the most characteristic feature of GCs. This anticorrelation was extensively studied among RGB stars by Kraft, Sneden and co-workers (see, e.g., Kraft, 1994) in the 1990s. As shown by Denisenkov & Denisenkova (1990) and Langer et al. (1993), this is evidence for material processed through high temperature H-burning in some of the GC stars (but not in the field stars). The O-Na (and equally the Mg-Al) anticorrelation is present in all GCs for which adequate data are available, and it is primordial, indicating pollution from other stars, as demonstrated by Gratton et al. (2001), who found that it also exists among MS stars (see also Carretta et al., 2004; and Ramirez & Cohen, 2002). While, in general, elements heavier than Al seem to have constant abundance ratios, Yong et al. (2008) found evidence for small variations in NGC 6752, although this result needs confirmation.

There are two main hypotheses for the polluting stars. Decressin et al. (2007) proposed that rotating massive stars (> 20 $M_\odot$) lose material through a dense, low velocity circumstellar disc. This mechanism is active on a short timescale (~ 10^7 yrs), resembling more a 'prolonged star formation' episode rather than two distinct episodes of star formation, and may even produce values of Y = 0.4; however there are difficulties in avoiding variations in [Fe/H], because of the contemporaneous explosion of core collapse SNe, and in producing clear sequences. Alternatively, stars with mass 5–8 $M_\odot$, which undergo hot-bottom burning during their AGB phase, are considered by Ventura et al. (2001). This mechanism is active on a longer timescale (~ 10^8 yrs), and it is a real case of 'two episodes of star formation'; there is no problem with [Fe/H] being constant, but apparently Y = 0.4 cannot be produced, and some tuning of convection and mass loss is required to reproduce the observed abundance pattern. Both mechanisms require

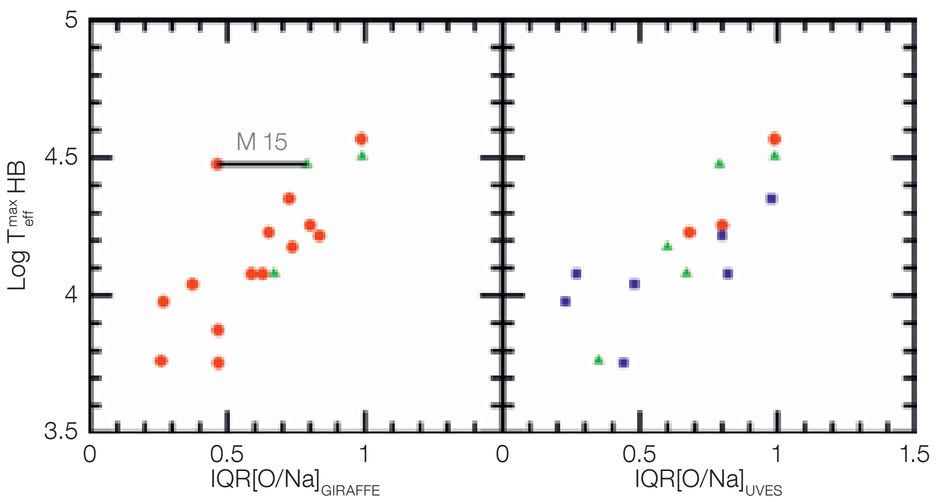

Figure 2. Maximum temperature of stars along the horizontal branch (HB) versus interquartile range (IQR) of the O-Na abundance distribution.

a very large primordial population that is then subsequently lost by the GC. A possible piece of evidence in favour of the AGB hypothesis is given by the observation of multiple turn-offs in LMC clusters (Mackey et al., 2008), with age spreads ~ 0.1–0.3 Gyr. These clusters are, however, less massive than typical GCs.

D'Antona et al. (2005) made an important breakthrough by recognising that the spreads in the He abundances imply different evolutionary masses, and thus the likely location of the stars along the HB. Extensive data for many GCs are required to confirm the relation between HBs and O-Na anticorrelation. The availability of FLAMES on the VLT has made such a study possible (the Na-O anticorrelation and HB (Naaah) survey) that was presented at this meeting by Carretta. GIRAFFE and UVES spectra were obtained for over 1200 giants in 19 GCs. A homogeneous analysis was performed and the GIRAFFE spectra provide good statistics for Na and O; in addition UVES spectra yield abundances for several elements. To define the extension of the O-Na anticorrelation, Carretta et al. considered the interquartile range (IQR), which they found to be correlated with the maximum effective temperature of stars on the HB (see Figure 2), confirming an earlier finding (Carretta et al., 2007b). The IQR is also correlated with cluster luminosity, which is itself correlated with the presence of hot stars on the HB, as noticed by Recio-Blanco et al. (2006). This finding may be explained by an increased ability for massive GCs to retain the original unpolluted stars. In fact, Carretta et al. also found that there are at least three populations in GCs: primordial population (P), intermediate population (I), and extreme O-poor population (E). P and I populations are present in all GCs, while the E population is present in only a few GCs. E and P populations are correlated with the IQR, while the I population is anticorrelated with the IQR. Notably, the three groups have the same [Fe/H] to within ~ 0.01 dex.

We conclude by noting that the evidence for the chemical evolution of GCs is now well established, although the details of the evolutionary processes that give rise to this situation are not yet clear. Massive GCs are very likely to have a close relation with UCDs, and even more probably with the nuclei of dwarf galaxies. Very important progress has been made recently thanks to the ACS camera on HST and the ESO VLT GIRAFFE and UVES spectrographs. We await new and exciting results from further use of these powerful instruments in the near future.

Acknowledgements

I wish to thank Eugenio Carretta and Angela Bragaglia, who are responsible for most of the new results presented in this discussion, and the meeting organisers for financial support.

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