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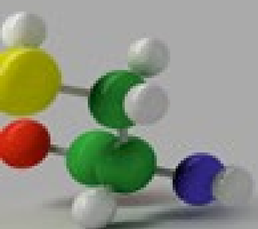
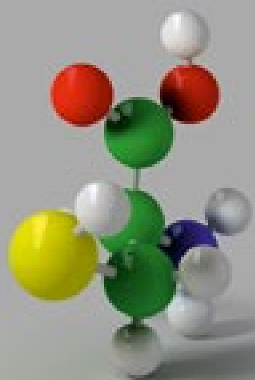
Chemical Evolution of Dwarf Galaxies and Stellar Clusters

Review Articles





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Special Report on the MPA/ESO/MPE/USM 2008 Joint Astronomy Conference

Chemical Evolution of Dwarf Galaxies and Stellar Clusters

held in Garching bei München, Germany, 21–25 July 2008

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It is our pleasure to celebrate the success of our 2008 summer conference with the publication of this special supplement issue, in which we have collected the articles of at least the majority of the review talks presented at the meeting.

The 2008 MPA/ESO/MPE/USM Joint Astronomy Conference focused on the chemical signatures and evolution of dwarf galaxies and stellar clusters. It took place in Garching at the end of July (21–25 July), and it was attended by 148 participants. There were no Proceedings, as the Local Organising Committee had decided to collect articles from the review speakers instead and have them published 'somehow' in the ESO Messenger. This 'somehow' has now become a special supplement to the December 2008 issue of the ESO Messenger.

The choice of the scientific topic of this year's Joint Astronomy Conference in Garching was driven by the current intensive work in determining stellar abundances in galactic stellar systems (notably globular clusters) and Local Group dwarf galaxies. Many of these projects are being actively pursued with the latest instruments, and have revealed surprising results. Abundances and kinematics are now routinely measured for hundreds of stars per galaxy/cluster, thanks to the latest generation of multiplex facilities. Our mapping of the Local Group is basically changing on a month-to-month basis (sometimes even more often), and the recent discovery of several ultra-faint dwarf galaxies clearly offers new horizons to explore.

As globular clusters and dwarf galaxies form a mass sequence, and possible connections between the two classes of stellar systems have always been proposed (e.g., globular clusters as the cores of former dwarf galaxies), a confrontation and comparison of cluster and dwarf galaxy chemical evolution appeared to be interesting and possibly helpful in understanding the origin of the abundances in both classes.

Indeed, the meeting turned out to be very lively and stimulating, with many interesting new results presented. So many that several review speakers mentioned that their presentations, especially in terms of number of known dwarf galaxies, were up-to-date 'only' until the week before the meeting, clearly demonstrating the incredible pace at which new ultra-faint galaxies are being discovered from the Sloan Digital Sky Survey.

All the major areas were covered by at least one review talk, followed by many invited and contributed presentations. This issue collects most of the review articles: from Mario Mateo's opening talk, to Raffaele Gratton's and Kim Venn's presentations on the chemical signatures of globular clusters and dwarf galaxies respectively; to Santi Cassisi's and Francesca D'Antona's reviews on how these abundances can be interpreted in terms of stellar evolution models and how they could be connected; and last, but not least, the concluding remarks by Ken Freeman.

Further, at the meeting, Eva Grebel investigated the links among ages, kinematics, metallicities and other properties of dwarf galaxies and presented the dynamical and chemical evolution of an isolated system with the properties of a self-gravitating three-component dwarf galaxy consisting of gas, stars and dark matter. Also, we heard a lot about the formation of stellar systems, in the nice reviews given by Pavel Kroupa and Oleg Gnedin, the latter broadcast via video-connection from Gnedin's home institution. Kroupa talked about the early evolution of dense stellar systems, its dependence on mass, and discussed some hitherto poorly understood scaling relations in the transition region between star clusters and dwarf galaxies. Gnedin presented an overview of the dynamical evolution of globular clusters and dwarf galaxies over cosmological timescales, with an emphasis on Local Group systems. He also described current ideas on the formation of massive star clusters in the first several gigayears after the Big Bang, as well as the latest models of star formation in small dark matter halos, which address the 'missing satellites problem' and help to explain the detailed star formation histories of dwarf galaxies in the Local Group.

All the presentations, including all the posters, are publicly available and linked from the conference website *http://www.mpa-garching.mpg.de/mpa/conferences/garcon08/*. This has also been a major accomplishment, and we would like to thank all participants and presenters publicly for having been so responsive to our calls for papers and presentations. Special thanks go to the review speakers who made it into this supplement issue. We know that the deadline was very tight, but our (now achieved) goal was to publish this supplement as close as possible to the time of the conference. Finally, our warm thanks go to all the students and technical/administrative supporters who have contributed to the success of this meeting.

Enjoy the reading!

Francesca and Achim

The Complex Evolution of Simple Systems

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The simplicity and extreme ages of globular clusters and dwarf galaxies imply that these systems may be useful windows to the earliest era of galaxy formation. Recent discoveries of local dwarfs have, in some ways, begun to blur the distinctions between the two types of systems. However, it remains clear that the two types of systems arose from fundamentally different conditions in the early Universe. Globular clusters result from 'intense' (what is often referred to as 'efficient') star formation processes, possibly related to major merging, while dwarf galaxies represent regions of much more 'sedate' (low efficiency) star formation, possibly independent of significant contributions from merging. I review spatial, kinematic and chemical results that support this interpretation.

What could be simpler? Collect enough gas – and possibly dark matter – in one region of space so that, even in the presence of Universal expansion and a hot cosmic background radiation field, it becomes Jeans unstable. If dense enough, the cloud forms individual stars that ultimately settle into a dynamically quasi-stable system in which the stars are distributed as expected in simple dynamical models (e.g., King, 1966). Really, what could be simpler? For decades, astronomers were certain that this basic picture accounted for the properties of globular clusters and, quite possibly, dwarf spheroidal galaxies, the recognised denizens of the low luminosity end of the population of spheroid systems (Figure 1 of Kormendy, 1985). In the past two and a half decades, we have come to realise that the simple appearance of dwarf spheroidal (dSph) galaxies belies a rich range of population, kinematic, environmental and chemical properties that are fundamentally at odds with the simple paradigm summarised above. More recently, some globular clusters – the very embodiment of simple stellar populations – have been observed to exhibit some bizarre properties that reveal unexpected similarities to dwarf galaxies, blurring the distinction between these two types of stellar systems.

Even if we acknowledge that low luminosity spheroidal systems and their cousins, the low luminosity dwarf irregular galaxies, are intriguing in their own right, then it is their role in bigger questions of structure formation that makes their study particularly compelling. Over the course of my astronomical career – and, really, it has not been *that* long! – the pendulum regarding the paradigm of galaxy formation has swung completely from one extreme to the other. The monolithic model, first expounded in detail by Eggen, Lynden-Bell & Sandage et al. (1962), has swung to models that incorporate fundamentally hierarchical processes, inspired by Searle & Zinn (1977), in which small structures form first, then merge to build up larger systems. Today, the hierarchical paradigm is unquestionably the more popular, and rightly so. We see direct evidence for mergers, most spectacularly in the form of streams and tidally disrupted dwarfs that are clearly contributing to the populations of local galaxies, including the Milky Way. Dwarf galaxies and globular clusters must play a central role in the hierarchical paradigm for a fundamental reason. These objects comprise the smallest and oldest systems surrounding present day galaxies. But small and old things must, at the very least, be contemporaneous with the hierarchical 'building blocks' that we now believe drove the formation of larger systems. Some of today's systems may even be identical to some of these early structures, but, due to chance, have not yet merged into larger galaxies. In these respects, the local dwarfs and globular clusters are identifiable fossils of the era of active galaxy formation, an era drastically unlike the present. Can we interpret the messages that these fossils contain?

Figure 1. An image showing a globular cluster (upper right), a dSph galaxy (lower right) and a galaxy, Fornax, that contains a (small) population of globular clusters (the numbered objects in the image to the left). Even here, the considerably higher surface brightness of the globular clusters, compared to the galaxies, is evident.

This paper is based on my opening talk at the very successful MPA/ESO/MPE/USM conference, "Chemical Evolution of Dwarf Galaxies and Stellar Clusters", held in Garching in late July 2008 (and skillfully organised by Achim Weiss and Francesca Primas, to whom I extend my thanks). I thought that I knew enough about both dwarf galaxies and globular clusters to contrast their properties effectively. Although there remain many fundamental differences between dwarfs and clusters that I outline below, the conference did reveal some unexpected traits that they share. This may have muddied our understanding in some areas that some people – at least me! – felt were converging to a fairly broad consensus. Perhaps the most telling example is the fact that there are now serious discussions about how we can conclusively distinguish clusters from low luminosity dwarfs near the various parameter interfaces that, until relatively recently, comfortably separated the two classes of objects. When the validity of the classification of (some) clusters and dwarfs are being called into question, you know things are getting pretty interesting. I will follow a similar outline in this paper that I used in my talk, but, where possible, incorporating some of the exciting new results and ideas that arose at the conference.

Clusters and galaxies: fundamentally different

There is no question that some of the distributions of properties of dwarf galaxies and clusters overlap, for example luminosity, baryonic mass, even kinematics. At the conference there was extensive discussion whether cluster and galaxy sizes overlap, given recent claims (for an example in the recent literature, see van den Bergh, 2008) that there is a "gap" between about 20–100 pc in the distributions of half-light radii in the two types of systems, with the clusters comprising the more compact population. Recent highly successful searches for new dwarfs and clusters have begun to populate the gap. The diffuse clusters of M31 (Mackey et al., 2006) and the very lowest luminosity dwarfs (Martin et al., 2008) found in the past few years (and months!) have certainly begun to reveal a possible overlap in the distributions of half-light radii. Indeed, in some cases it is becoming a problem to know what classification to apply to individual systems. Some discussions of this distinction in classifying specific systems have been a bit arbitrary, while others have aimed at determining more objective criteria applicable to low luminosity systems. This is not easy: some systems have integrated luminosities comparable to those of individual red giant stars, which can lead to large Poisson uncertainties in their luminosities and structural properties, as nicely illustrated by Martin et al. (2008).

Despite the overlap in some of their properties, there is little question, in my view, that dwarf galaxies and globulars are fundamentally different sorts of stellar systems. One of the most obvious hints of this comes from their relative distributions around the Milky Way. Figures 2–4 show the spatial distributions of Galactic globular clusters (data from Bill Harris's online compilation of GC properties) and dwarf satellite galaxies of the Milky Way (data from Mateo, 1998), supplemented fully with recent data for systems discovered through July 2008). Around the Milky Way (Figures 2–3) it is clear that the distributions of clusters and dwarf galaxies are almost mutually exclusive. Whereas the median Galactocentric distance of globular clusters is smaller than the Sun's, the objects we consider to be dwarf galaxies strongly favour the remote halo. Only a few recently discovered, very low luminosity systems, streams, or possibly unbound shreds exist within an effective 'no-fly' zone out to about 70 kpc (Figure 3). This distribution suggests that the smallest dwarfs are strongly influenced by tidal effects that either disrupt or transform them drastically inside this zone (e.g., Mayer et al., 2006). The Magellanic Clouds are an obvious exception, but recent proper motion measurements (Kallivayalil et al., 2006; Piatek et al., 2008) suggest they are passing by the Milky Way for the first time. If true, they are not really yet part of the Galaxy and, given their comparatively large masses, have not yet interacted strongly with the Milky Way. What is also clear (Figure 4) is that the population of dwarf galaxies itself changes with Galactocentric distance. Between 70–250 kpc, the dwarf population is dominated by spheroidal systems. Beyond this outer radius, dwarf irregular (dIrr) galaxies (again, the Magellanic Clouds excepted) dominate the population of Local Group dwarfs. This basic segregation of dwarf/cluster properties with Galactocentric distance has been commented upon for some time in the literature (van den Bergh, 1994).

Figure 5 illustrates the distribution of the ages of the youngest populations in individual galaxies as a function of Galactocentric distance. Only some of the more critical, recently discovered galaxies, Leo T and And XVIII for example, are included in this figure, but there is no qualitative change to Figure 5 if all of the 'newer' dwarfs are included. The distribution of the youngest ages reveals the same effect we saw more qualitatively in Figure 4. Unless we have been very lucky with the ensemble of dwarf galaxies in the outskirts of the Local Group, Figure 5 implies that such galaxies have probably been forming stars at the low rates we see today over much of their history. I like to call this process 'percolation', and it seems to represent the mode of star formation one can expect in low mass, gas-rich and tidally undisturbed systems. Many of the dIrr galaxies of the outer Local Group can continue to form stars as they do now far into the future. The lack of any clear examples of 'red and dead' systems with clear disc kinematics suggests, moreover, that no such percolating galaxies have yet died a natural death by consuming all their gas in star formation (though in the light of our lack of information regarding the internal kinematics of Tucana and Cetus, the two outliers in Figure 5, we do not know if these may be examples of such deceased dIrr galaxies). Overall, the spatial distribution and populations of dwarfs apparent in Figures 4–5 are consistent with a model in which tidal effects drive the evolution of these systems.

The really obvious distinction between clusters and dwarfs, however, is most strikingly apparent when we consider their surface brightnesses, a point that has been known for quite some time (Kormendy, 1985). Although sizes, luminosities and even kinematic properties overlap among the two populations, the surface brightnesses do not; this is graphically apparent in Figure 1, where the globular clusters of one dwarf, Fornax, a comparatively high surface brightness example of its class, are readily evident due to their elevated surface brightnesses compared to the field stars in the galaxy. In his excellent review at the meeting, Oleg Gnedin emphasised this point and noted that this strongly suggests fundamentally different modes of star formation in dwarf galaxies and globulars.

I would go just a bit further with this idea. The clear segregation of dwarfs by type, and of dwarf galaxies from clusters (Figures 2–4), suggest that the modes of star formation were of relatively differing importance at different stages of the formation of the Milky Way. One can imagine, for example, that the initial overdensity in the matter distribution that grew eventually into our Galaxy consisted of a lot of gas, undifferentiated and tidally disturbed dark halos, but perhaps a few or none of the classical independent hierarchical building blocks we might imagine to have preceded the formation of the Milky Way. At such times, star formation was probably driven more by strong gas interactions (cloud–cloud collisions, wind-driven shocks, supernova compression) than mergers of mature, star-bearing systems. This scenario would favour intense star formation and considerable supernova chemical signatures.

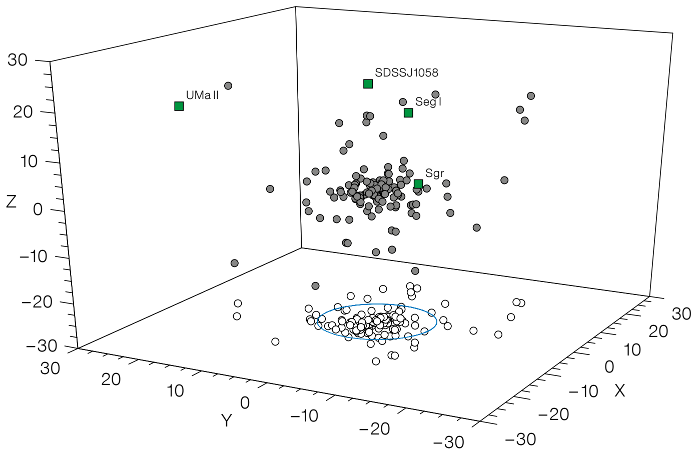

Figure 2. The distribution of inner halo objects as a function of Galactic X, Y and Z coordinates. Grey points are globular clusters, while the green points represent the closest of the recently discovered dwarfs, as well as the Sgr dwarf. Note that nearly all the objects in the inner halo are globulars; their median distance from the Galactic Centre is smaller than the Sun's (as shown by the ring of the Solar Circle in projection along the bottom of the plot). The open dots are the positions of the globular clusters projected down to the x-y plane.

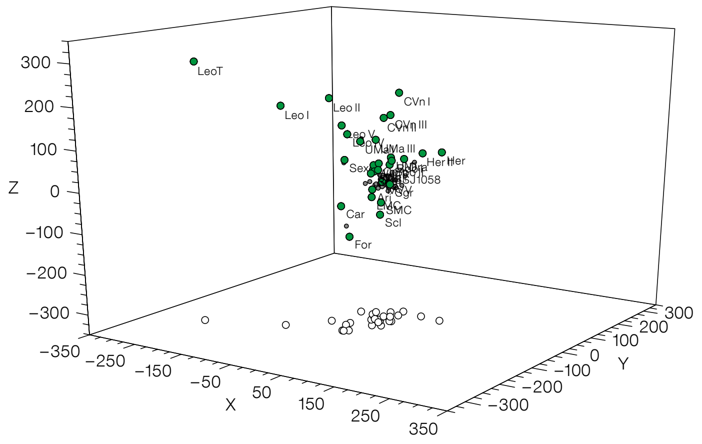

Figure 3. The distibution of objects in the outer Galactic halo. Individual dwarfs are shown as green dots and are labelled by name. The projected positions in the x-y plane are shown at the bottom of the plot as open circles. The asymmetric distribution apparent here is largely due to the uneven sampling imposed by the SDSS.

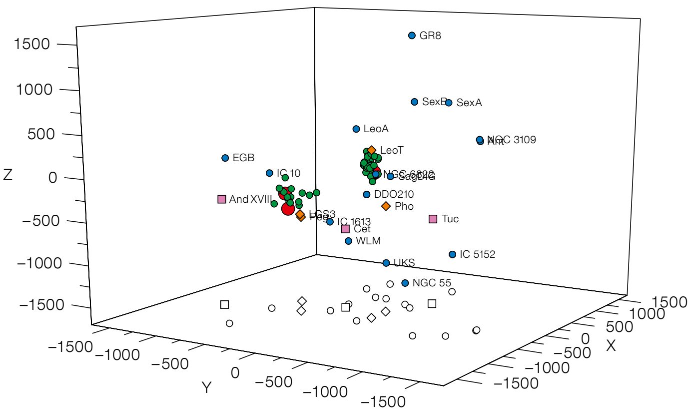

Figure 4. The distribution of all galaxies in the Local Group. Green dots are the dSph galaxies; blue dots the dIrr galaxies. Orange diamonds represent the so-called transition galaxies (see Mateo, 1998), while three remote dSph galaxies are shown as pink squares (Cetus, Tucana and And XVIII). The large red dots are M31, the Milky Way and M33. The projected distribution in the x-y plane of all the galaxies except the dSph systems is shown at the bottom of the plot with open symbols. Note that while the clustering of the dSph galaxies is obvious in this plot, the projected distribution reveals that the dIrr and transition systems are not at all clustered on M31 or the Milky Way.

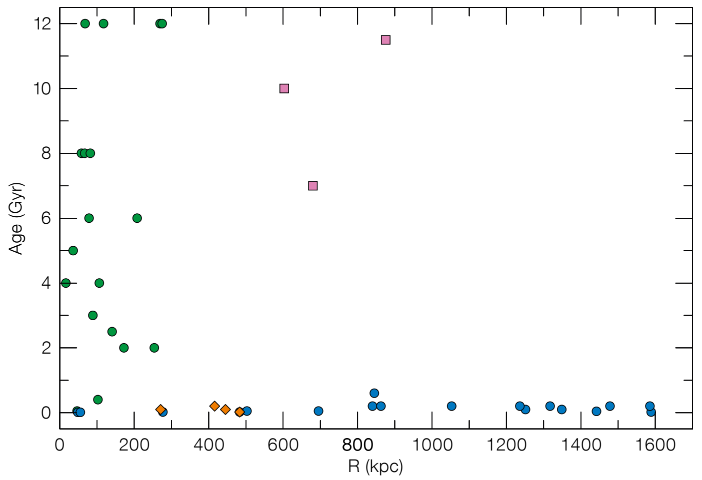

Figure 5. A plot of the ages of the youngest populations as a function of Galactocentric (or, where appropriate, M31-centric) distance (RGC) for Local Group dwarfs. The symbols are the same as in Figure 4. Note the clear progression from dSph, to transition, to dIrr galaxies with increasing RGC. Star formation is preferentially truncated near massive parent galaxies.

Globular clusters probably represent this form of star formation for two reasons. First, they likely could only form this way; the Antennae galaxy (Figure 8) represents a local example where a violent merger is actively producing massive, compact clusters in the interfaces where dense clouds are interacting (Whitmore, 2002). Second, structures that may have formed at lower density have long ago been disrupted and become part of the overall field of the Galactic Bulge.

Throughout the meeting we heard of this mode of star formation in globular clusters as being 'efficient', but we do not know if that efficiency should be defined as the fraction of gas in an initial star-forming event that is converted into stars. I would suggest that the term 'intense' is a better label for this mode and it can even be quantified by a star formation rate. We know that for some clusters with little or no age spread (not some of the perplexing cases presented at the meeting) that such rates would have exceeded 10–100 $M_{\odot}$/yr!

By contrast, dwarf galaxies represent cases where, for the most part, truly independent hierarchical structures were able to form stars and even evolve chemically over a significant amount of time. A few of these – Sagittarius is a clear example – may subsequently dissolve into a larger parent galaxy, but the mode in which the hierarchical process proceeds is quite different from that which must have occurred early on in a massive galaxy such as ours. Moreover, these independent structures produced stars in a much milder manner. If the remote dIrr galaxies are representative, then, left to themselves such galaxies form stars at a rate of more than 10^5 times lower than that which must have occurred in typical globular clusters. Dwarfs clearly represent the 'low intensity' mode of star formation.

A curious implication of this has to do with the few dwarfs that have clusters (e.g., Fornax, Sagittarius, NGC 6822 in the Local Group). If the two modes of star formation – high and low intensity – are traced by globular clusters and the general field star formation in dwarf galaxies, respectively, then these galaxies must have experienced both. Generally, dwarf galaxies that do contain globular clusters are among the more massive systems. This may just be telling us of the hierarchical processes, similar to the gas-rich phase described above for the Milky Way, that were going on early in the formation process of these galaxies. How the massive nuclei of some dwarf galaxies fit into this picture is unclear, but the complex star formation history of ω Centauri, a fascinating topic of this meeting, may be a clue that these objects form in some hybrid manner in which distinct, intense bursts of star formation can occur over an extended timescale.

Chemistry in dwarf galaxies

A fundamental topic of this meeting concerned the chemical evolution of dwarfs and clusters. Here again, clusters and dwarfs reveal some telling differences. Perhaps the best known is the well-established lack of enhancement (relative to iron) of α-elements of the stars in dwarf galaxies compared to metal-poor globular clusters (e.g., Pritzl et al., 2005). Canonical chemical evolution models attribute this enhancement to Type II SNe during the peak star formation epochs in a given population. The distinction between dwarfs and clusters appears to suggest that, while globular clusters were either self-enriched in α-elements or formed from material already enriched in these elements, dwarfs formed neither from such gas nor did they produce much additional α-enriched gas that could pollute subsequent generations. What is perplexing about this is that for most globular clusters, the star formation epoch was very short, so the window for self-enrichment is short. The fact that massive stars form first in most models of star formation helps this self-enrichment to occur. However, in contrast, star formation is demonstrably extended in nature in most dwarf galaxies and so if *any* SNe enriched the gas in these systems, it would reveal itself to us today in the detailed α-abundances. One has to conclude that *no* Type II SNe occurred during any of the star formation events in dSphs, or that the gas was mixed in such a way as to concentrate the enhancement quite nonuniformly and in stars that we have, by chance, not observed yet. This represents another important distinction between the high intensity star formation mode characterised by globular clusters and the low intensity mode of dwarfs, implying that in the low intensity mode the formation of very massive stars may be strongly suppressed, not merely statistically unusual. If the initial mass function (IMF) is a purely statistical distribution, then a series of N star-forming events that produce M solar masses of stars each should produce as many massive stars as a single event that produces M × N solar masses in stars. The abundances of the α-elements in dwarfs suggests this is *not* the case and that high-mass star formation has a minimum threshold in some key regulating parameter (Star formation intensity? Overall mass of the star-forming region?). In this respect, a comparison between the α-abundances of the field stars and of the members of the globular clusters in Fornax would be most interesting.

Another key chemical difference between globular clusters and dwarf galaxies is apparent when we consider their mean abundances as a function of baryonic content. It is well known that among globular clusters there is no relation between cluster luminosity and mean abundance. The full range of chemical abundances exhibited by clusters are apparent when one considers only the most luminous clusters (e.g., 47 Tuc, (M_V, [Fe/H]) = (−9.4, −0.8) and NGC 2419 (−9.6, −2.1)) or the least luminous clusters (e.g., NGC 5053 (−6.7, −2.3) and Ter 3 (−4.5, −0.7)). This suggests that their mean abundances were dictated by largely external processes or initial conditions and not by self-enrichment by their own stars during the periods when they formed their stars. We were reminded of some intriguing clusters during the meeting (ω Centauri, long known to be unusual, but also NGC 2808, M54 and others), but it seems that even in these cases the chemical anomalies that are present may reflect processes that either occurred outside the clusters, or before they were born. This topic led to animated discussion during the conference!

By contrast, dwarf galaxies reveal a strong correlation of luminosity and mean chemical abundance, a key point first noted some time ago by Skillman et al. (1989). Figure 6 shows a modern com-

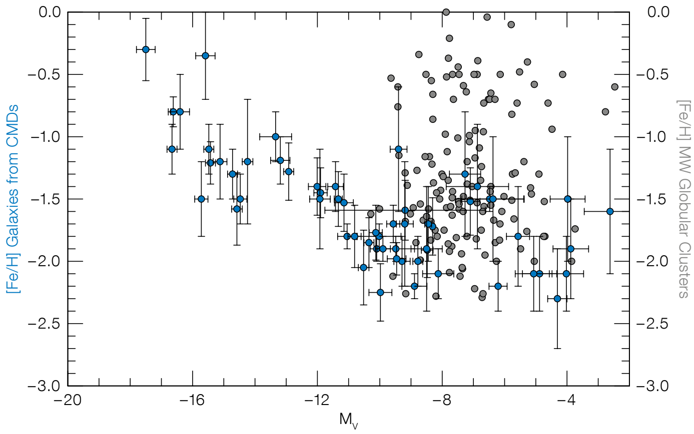

Figure 6. The age-metallicity relation for dwarf galaxies of the Local Group (blue dots) and Galactic globular clusters (grey dots). The mean metallicities of the galaxies are from CMD analyses, with no cuts on the quality of the measurements. Do the dwarfs transition into the clusters in this diagram?

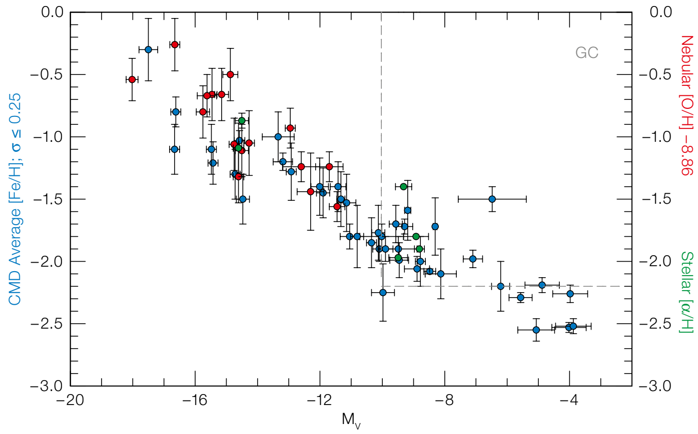

Figure 7. The age-metallicity relation for dwarf galaxies of the Local Group from high quality CMD and spectral analyses ($\sigma_{[O/Fe]} \leq 0.25$ mag; blue dots), nebular abundances (on a scale set by the solar [O/Fe] value; red dots), and from stellar α-abundances (green dots). The realm of globular clusters is denoted by the grey dashed lines (see Figure 6). Here it is more apparent that the galaxy abundance trend seems to pass through, and is independent of, the cluster distribution.

pilation of the chemical abundances – determined from photometric indices such as colour-magnitude diagrams (CMDs) – and luminosities for the many Local Group dwarfs for which good data exist. Many details went into producing this plot, but for our purposes the abundances plotted can be assumed to approximate the modes of the distribution of abundances in the individual galaxies. For reference, the most luminous galaxy plotted in Figure 6 (and all subsequent plots of this type) is the Large Magellanic Cloud (LMC); the least luminous objects are all recent discoveries, some of which are considerably less luminous than the Pleiades, a few less luminous than a single asymptotic giant branch (AGB) star! Figure 6 reveals the classical trend of lower metallicity with decreasing luminosity, but with what appears to be a saturation setting in at a mimimum metallicity of about −2.2. The latter point has been noted by Helmi et al. (2006) as evidence for the existence of a floor in the metallicities of dwarf galaxies.

We can do better, however. In recent years there has been a very impressive effort to obtain spectral abundances of individual stars in dwarfs; we heard about many of these studies at the meeting. Collectively, this work represents a fantastic and extremely important addition to our understanding of the basic properties of these galaxies. Figure 7 updates the luminosity-metallicity relation of Figure 6 with these spectroscopic abundance measurements, both of stars and H II regions where applicable. Again, the details of this plot are complicated, but the points represent careful means of spectroscopic estimates from stars or gas for each galaxy, often from multiple sources. The resulting distribution now reveals a remarkably tight, essentially linear relation between Log L and [Fe/H] over a factor of more than a million in galaxy luminosity! Note too that the [O/H] abundances obey the same trend with no shift, a distinction from previous results (Mateo, 1998; Grebel et al., 2006) and are consistent with the recent findings that the α-elements are not generally enhanced in the stars of these galaxies. In Figure 7 there is now no hint of a saturation at low abundance, a result that is almost entirely due to the new abundances of the faintest dwarfs from Kirby et al. (2008) that we heard quite a lot about at the conference.

Figure 7 is astonishing in many respects. Some galaxies plotted here still have gas and are forming stars, so their abundances and luminosities are changing. The implication is that dwarfs evolve in such a way that *they remain on the L-[Fe/H] relation at all times*. The overall relation also suggests that self-enrich-

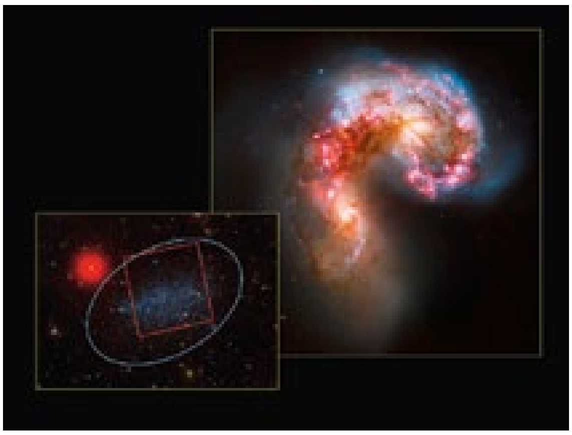

Figure 8. Dwarf galaxies seem to have followed comparatively sedate star formation histories, devoid of much contamination by supernovae (left). Globular clusters seem to have formed in far more violent conditions (right). Together, they may allow us to piece together many of the key elements of galaxy formation.

ment is important for dwarfs as they occur along a line that is consistent with internal, but truncated chemical enhancement (Dekel and Silk, 1986). However, we know that many of these dwarfs have complex star formation histories, including many that have no gas today. Thus, the classical ideas that SNe blew out gas in these systems to halt their star formation and chemical enhancement is simply wrong, a conclusion consistent with the α-abundances summarised above. Instead, the evolution implied by Figure 7 is of a classical closed box (although perhaps underaffected by SNII enrichment compared to, say, a region in a massive disc galaxy such as the Milky Way) that either continues to form stars at, generally, very low rates from self-enriched gas (the dIrr systems), or implies a system in which the gas was removed rather suddenly before it could all be cycled into stars (the dSph galaxies). The latter process is likely to be external (e.g., Mayer et al., 2006), since the chemical signatures of SN winds appear to be absent.

I have intentionally kept silent in this discussion regarding the *distribution* of metallicities in dwarf galaxies. Kirby et al. (2008) comment on this, particularly for the lower luminosity systems plotted in Figure 7. The key point that emerges is that all of these galaxies appear to possess a significant range of chemical abundances, sometimes only a factor of 2–3, sometimes up to a factor of 20, but not obviously correlated with luminosity. My guess is that these abundance spreads reflect the extended nature of star and chemical evolution in these galaxies, and (possibly in addition to the first effect) inhomgeneities of the chemical properties of the gas from which these systems formed (see below). We also heard at the conference about extremely intriguing results regarding α-abundances of stars in some of the least luminous galaxies known. In a number of these cases, it appears that there *are* α-element abundances of about 0.5 dex above solar, similar to that seen in halo stars, but not in more luminous dwarf galaxies. If these enhancements reveal enrichment due to very early Type II SNe, why do we see these only in the lowest luminosity dwarfs? Note that from Figure 7 the mean abundances of these galaxies are around 2.5 or lower; some of the iron abundances of the individual stars measured in these galaxies and ones that exhibit α-enhancement are 3.0 or lower. Boosting O abundances by a factor of three requires adding only about three Earth masses of that element to a solar-mass star! Such a tiny enhancement would be hard to detect in higher metallicity stars, but is apparent in very metal-poor objects. Are we seeing the (faint) chemical echoes of the very first supernovae of the first stars that enriched the gas from which dwarf galaxies formed?

Small objects, big implications

Spatial distribution. Chemistry. I have only focused on two major areas in which clusters and galaxies clearly differ, pointing out that these differences imply further fundamental distinctions in how these objects formed. There are other important distinctions, dark matter content perhaps being the most significant. We heard talks that addressed these other areas of contrast between clusters and galaxies. We heard that there may be a significant number of clusters that evolved in galaxy environments, leading to unusual internal age and metallicity distributions. This points to a common origin, at least in some cases, between clusters and their parent galaxies, and seems to have produced some clusters with populations reminiscent of galactic systems rather than the unimodal populations we are used to seeing in most other clusters.

To reiterate a point that I made at the start, what we do know is that all the local dwarf galaxies, and most of the globular clusters, were around at the very earliest eras of star formation in the Universe. In globular clusters we generally see these ancient populations directly, although some clusters clearly formed at later times as we heard from summaries of recent Hubble Space Telescope/Advanced Camera for Surveys (HST/ACS) ages for globulars. Among the galaxies, we find that *there are no examples of any dwarf systems that do not contain an 'ancient' population of stars*. These little systems remain the closest survivors today that witnessed the era of star and galaxy formation so long ago.

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

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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.,

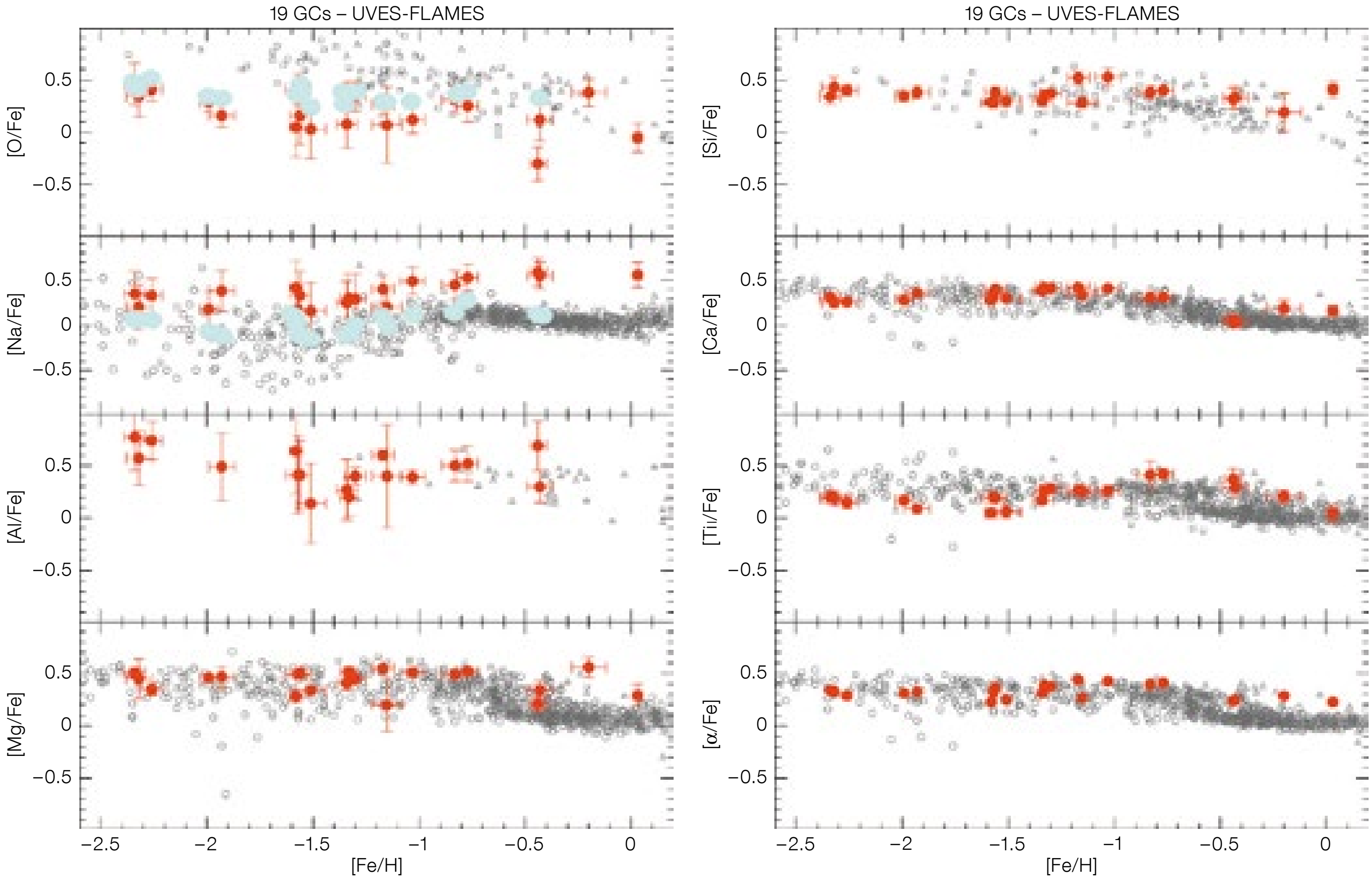

Figure 1. Abundances as a function of the metallicity [Fe/H] for GC stars (Carretta et al.: red-filled symbols) compared with those of field halo stars from the compilation by Venn et al. (2004), as grey circles. Only O, Na and other α-elements are shown. For O and Na, abundances of the primordial population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

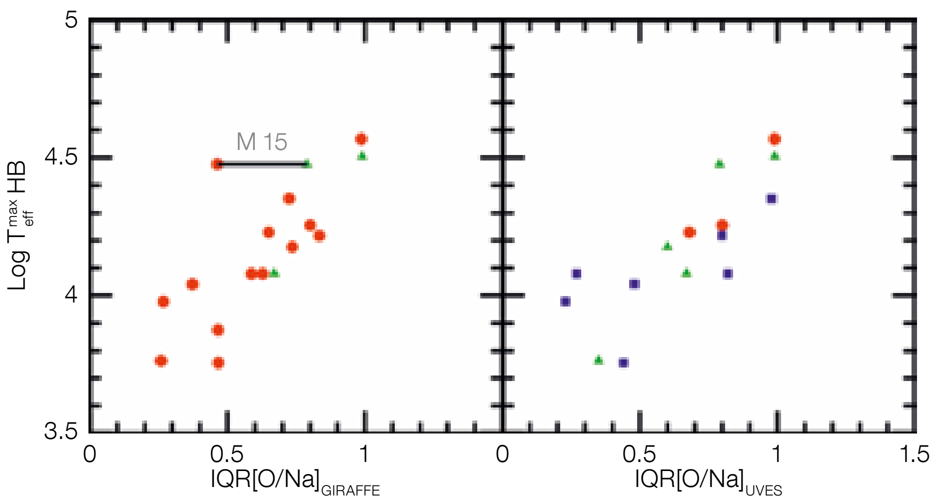

Figure 2. Maximum temperature of stars along the horizontal branch (HB) versus interquartile range (IQR) of the O-Na abundance distribution.

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.

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Evidence for Sub-Populations in Globular Clusters: Their Properties and Relationship with Cluster Properties

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An increasing number of both photometric and spectroscopic observations over the last decade have shown the existence of distinct sub-populations in some Galactic globular clusters. This evidence severely challenges the paradigm of globular clusters as the prototypes of single, simple stellar populations. In this review, we briefly summarise the main empirical findings collected so far and discuss the properties of these sub-populations and their possible relationship with global cluster properties.

The scientific framework

Globular clusters (GCs) still occupy a pivotal role in current astrophysical research. As the oldest population II objects for which accurate ages can be inferred, they place an important constraint on the age of the Universe and, in turn, on cosmology. In addition, the analysis of the chronology of the Galactic GC system can provide fundamental information on the formation process of the Galaxy.
For a long time GCs have represented an ideal laboratory for testing and calibrating stellar evolutionary models. In addition, since they are regarded as consisting of coeval and chemically homogeneous stars, they have been considered as the prototype of Simple Stellar Populations (SSP). In consequence, GCs have been employed as an ideal template for checking the accuracy and reliability of the population synthesis tools that are used to retrieve the properties of unresolved stellar populations.

Up until a few years ago the interpretation of the available colour-magnitude diagrams (CMDs) of GCs in the framework of theoretical stellar evolution fully supported the view of GCs as SSP (see, for instance, King et al., 1998). However there is a growing body of empirical findings that severely challenges this traditional view. In fact, accurate spectroscopic surveys of sizable samples of GC stars made after 1980 have revealed that GCs show a peculiar pattern in their chemical abundances: while they are generally – with very few exceptions – very homogeneous in the abundances of Fe-peak elements, GC stars show very clear anticorrelations between the abundances of C and N, Na and O, Mg and Al (for a full review of this issue we refer to Gratton et al., 2004) that are not predicted by canonical stellar models. It is worth noting that this pattern is characteristic of GC stars, since, in field stars, the observed trend for C and N abundances is consistent with the theoretical evolutionary predictions. This occurrence strongly supports the idea that the GC environment must play a role in the appearance of these chemical peculiarities. More importantly, accurate spectroscopic measurements of both dwarf and giant stars in GCs show that the observed chemical pattern is primordial, as it is also present in unevolved stars (Gratton et al., 2001), and, does not only involve the envelopes of the stars, i.e., it is not a simple pollution effect (Cohen et al., 2002).

Although there is no doubt that the observed anticorrelations are due to the fact that a fraction of the GC stars have formed from matter that has been polluted with the yields of high temperature H-burning (see Salaris et al., 2002, for a review), there is still some debate about what is responsible for this pollution: asymptotic giant branch (AGB) stars (Ventura et al., 2001) or fast-rotating massive stars (Decressin et al., 2007).

Many GCs also show a very peculiar Horizontal Branch (HB), with the presence of an extended blue tail (Recio-Blanco et al., 2006) and/or a clumpy distribution of stars characterised by the presence of one or more gaps (Ferraro et al., 1998; Piotto et al., 1999). These peculiarities in the horizontal branch morphology are commonly known as 'the second parameter problem', and we have not yet achieved a full understanding of their origin. In recent times the existence of a possible link between the HB morphology and the peculiar chemical patterns has been suggested (D'Antona & Caloi, 2004): matter processed via high temperature H-burning should also be enriched in He content, and it is known that a change in the initial abundance of He produces remarkable changes in stellar properties at the HB stage.

Thus, several independent observational findings seem to suggest that, at least in some GCs, there is a sizable fraction of stars that have formed from material that must have undergone nuclear processing by a previous generation of stars. In this context, it is clear that the fundamental question is whether we can find direct, straightforward evidence for the existence of multi-populations in some GCs?

Over the last few years, the availability of high quality photometry on deep HST images and multi-object spectroscopy has provided this evidence. So far, the presence of different sub-populations has only been proved in a few clusters, but the search is still ongoing and there are other GCs that are thought to host multiple populations. In the following, we briefly summarise the evidence collected so far for multi-populations, and discuss the possible link with the global properties of the parent GC.

The chief suspects: direct, observational evidence for multi-populations in GCs

The GCs in which indisputable, direct evidence of the presence of multiple populations has been found, are: ω Centauri, NGC 2808, NGC 1851, NGC 6121, NGC 6388 and M54. The last is considered to be the compact nucleus of the dwarf galaxy Sagittarius, currently being accreted by the Milky Way. However it is still under debate which of the sequences observed in the CMD of M54 represents the true cluster population and which are due to stars belonging to Sagittarius dwarf (Siegel et al., 2007). For this reason, we will not discuss this GC further.

ω Centauri

The observational evidence collected over the last 40 years indicates that this GC is the most peculiar object among Galactic GCs in terms of structure, kinematics and stellar content. It is the only known GC showing a clear metallicity spread and it is the most massive one. In the last decade, both extensive spectroscopic and photometric surveys on large samples of giant stars have shown that the distribution of stars in metallicity, as well as in colour, along the red giant branch (RGB) is clearly multi modal (Pancino et al., 2000; Sollima et al., 2005; and references therein), as shown in Figure 1. Specifically, Pancino et al. (2000) have shown the presence of a peculiar RGB (the so-called RGB-a), associated with a metal-rich population ([Fe/H] ~ –0.6) that corresponds to about 5 % of the whole cluster stellar population. Sollima et al. (2005) have identified three metal-intermediate components (–1.3 < [Fe/H] < –1.0) in addition to the dominant population ([Fe/H] ~ –1.6).

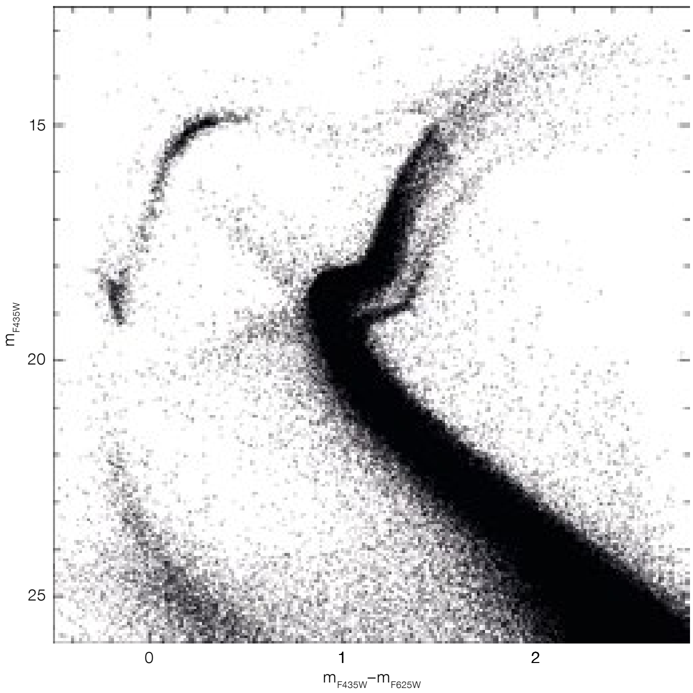

Figure 1. The colour-magnitude diagram of ω Centauri (from Villanova et al., 2007).

Accurate observational analysis has shown that some significant differences do exist among the metal-rich, the metal-intermediate and the metal-poor components, as far as both the spatial distribution (Pancino et al., 2003) and the kinematical properties (Ferraro et al., 2002) are concerned, although Pancino et al. (2007) found no evidence of a difference in the rotational pattern among the various sub-populations. Sollima et al. (2005) obtained the same result for the radial velocity distribution, but they also discovered that the metal-rich component shows a larger velocity dispersion, thus appearing kinematically warmer than the metal-intermediate sub-population.

The most surprising recent result was the discovery by Bedin et al. (2004; but see also Anderson, 1997) that, over a range of at least two magnitudes, the Main Sequence (MS) splits into a red sequence and a blue sequence. Follow-up spectroscopic analysis from GIRAFFE on the VLT (Piotto et al., 2005) leads to even more intriguing results: at odds with any expectations from canonical stellar models, the bluer sequence is more metal-rich than the red one. Until now, the only plausible explanation of the photometric and spectroscopic properties of the double MS is that the blue MS is populated by stars with a high helium content of Y ~ 0.38 (Norris, 2004; Piotto et al., 2005; Lee et al., 2005).

One of the main problems with this scenario is identifying the mechanism responsible for this huge production of helium. So far, various helium producers have been proposed, such as AGB stars (e.g., Ventura & D'Antona, 2008, and references therein), massive rotating stars (Decressin et al., 2007) or even population III stars (Choi & Yi, 2007). However, the properties of He-enriched populations appear to leave only the AGB scenario as viable, even if it still faces some quantitative difficulties (Renzini, 2008).

Even just a few years ago, only rough estimates of the relative ages of the sub-populations hosted by ω Centauri had been obtained, using broad- and narrowband photometry (see for instance, Hughes et al., 2004, and references therein). Recently, however, more detailed analyses have been performed by taking advantage of the most up-to-date photometric and spectroscopic observational facilities (Sollima et al., 2005; Stanford et al., 2006; Villanova et al., 2007; Calamida et al., 2008). The various investigations have obtained quite different, if not contradictory, results concerning the age-metallicity relation: in some cases no age difference is obtained for the different sub-populations; in other cases the metal-rich component is found to be younger by about 2–4 Gyrs with respect to the more metal-poor component; finally independent studies have found the existence of a significant age spread among the metal-poor and metal-intermediate components, with the metal-rich one being the older sub-population. It is worth noting that these different results could partially be accounted for by the fact that different regions of the clusters are sampled in the various analyses, and that the presence of a population gradient in ω Centauri is well-established. In addition, part of the difference in the age results can be attributed to the different theoretical frameworks, distance and reddening estimates used in the various analyses.

It is evident that a detailed study of the chemical abundances and a more complete photometric sampling of the different sub-populations identified in ω Centauri is badly needed in order to understand the complex star formation history of this cluster better.

NGC 2808

This GC is one of the most peculiar Galactic clusters in many respects: for a long time the morphology of its HB has been known to be highly bimodal, with the presence of one or more gaps in the stellar distribution (Bedin et al., 2000); it presents – together with M13 – the strongest O-Na anticorrelation among the Galactic GC population. In addition, Carretta et al. (2006) have shown that it is possible to identify three different subgroups of RGB stars on the basis of their O abundances: O-normal, O-poor and super O-poor components. On the basis of the possible existence of a correlation between O and He content, one can hypothesise the existence in this GC of three distinct sub-populations of stars, each characterised by a different He content. A direct comparison between the star counts for the different stellar groups along the HB, and the sub-groups identified by Carretta et al. (2006), shows the presence of a rather straightforward correspondence between the stars along the RGB and their progeny on the HB: the red HB stars would be those that formed with O-rich/Na-poor/He-poor composition, while the other two groups of RGB stars would contribute to forming the stars that populate the hottest portion of the HB.

However, the most amazing result was the discovery by Piotto et al. (2007) that the MS of NGC 2808 is split into three loci. The unique scenario found for interpreting this occurrence is to assume that the three MSs correspond to stars with three different He contents (see Figure 2). The self-consistency of this interpretation with the empirical evidence collected for both RGB and HB stars is really intriguing.

This GC, which clearly hosts multiple stellar populations, is the most massive one after ω Centauri.

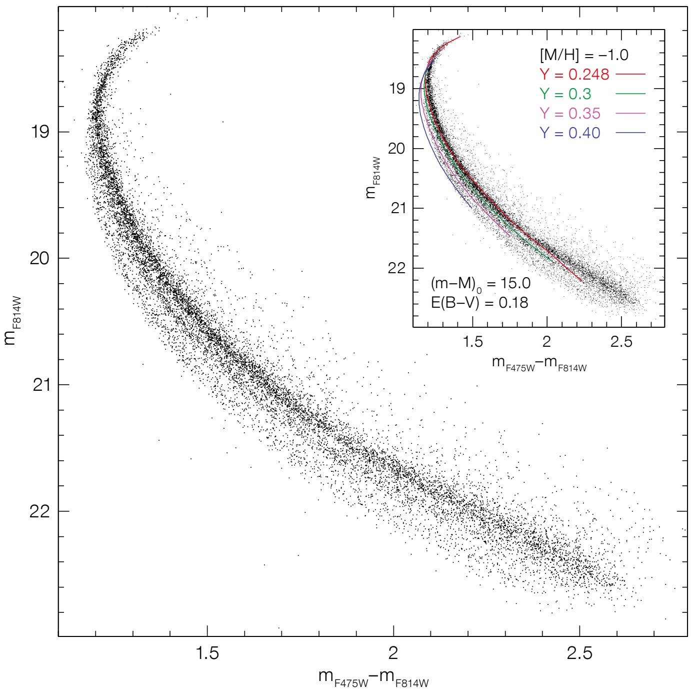

Figure 2. The triple main sequence of NGC 2808. The inset shows the comparison with suitable sets of isochrones computed for different assumptions on the initial helium content (from Piotto et al., 2007).

NGC 1851

Accurate HST/ACS photometric data have provided indisputable evidence that this cluster hosts at least two distinct sub-populations (Milone et al., 2008): there is a clear splitting in the sub-giant branch (SGB) region (see Figure 3) in its CMD. If the brightness difference between the two SGBs were due only to an age difference, the two star formation episodes should have occurred with a time delay of about 1 Gyr. However, Cassisi et al. (2008) have shown that the presence of two stellar populations in this GC, one with a normal α-enhanced heavy element distribution, and one characterised by a strong CNONa anticorrelation pattern, could properly account for the observed SGB splitting, without invoking any significant age difference. Interestingly enough, this working scenario seems to be supported by spectroscopic measurements (Hesser et al., 1982) indicating the presence of two groups of stars (CN-strong and CN-weak) and by the recent works by

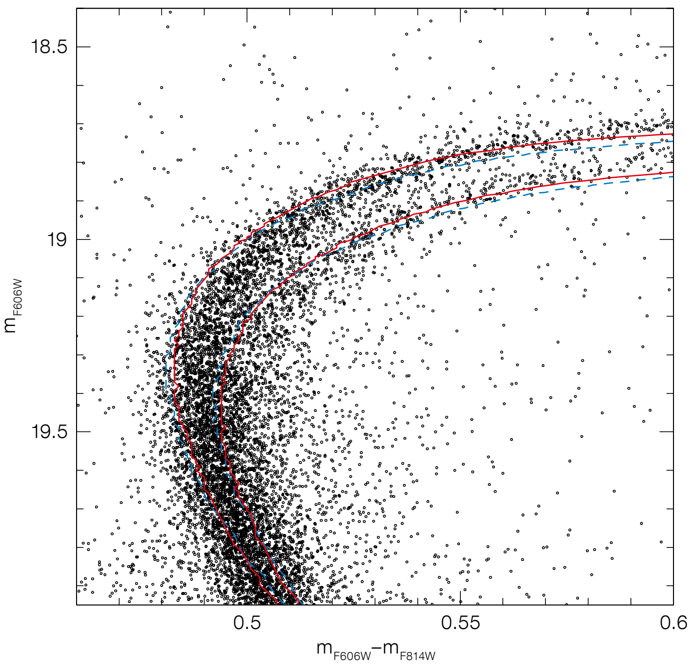

Figure 3. The colour-magnitude diagram of NGC 1851 zoomed around the sub-giant branch. The solid lines represent the isochrones for a stellar population with extreme CNONa anticorrelations and ages of 9 and 10 Gyr. The dashed lines correspond to isochrones for a population with a normal α-enhanced chemical composition and ages of 10 and 11 Gyr.

Yong & Grundahl (2008) and Calamida et al. (2007).

NGC 1851 is considered to be the prototype of bimodal HB GCs. It is intriguing to note that the star counts along the two different SGBs are in remarkably good agreement with those of stars belonging to the two main groups of HB stars. Therefore, one is tempted to look for a link between the different SGB sub-populations among the two groups of RGB stars with distinct CN abundances and the HB stellar sub-populations. In any case, it is evident from both the observed MS width (Milone et al., 2008) and from HB synthetic models (Salaris et al., 2008) that the He enhancement, if any, between the two sub-populations has to be very small (less than 0.03).

Direct spectroscopic measurements of the SGB and HB stars, as well as studies of the mass-loss efficiency among the RGB stars in NGC 1851 (see Salaris et al., 2008, for a discussion on this issue), are mandatory.

NGC 6388

This GC and its twin cluster NGC 6441 are two extremely peculiar clusters. Despite their high metallicity – larger than that of 47 Tuc – they show a bimodal HB, extending towards very hot effective temperatures, a tilt in brightness (Rich et al., 1997; Busso et al., 2007), and a Na-O anticorrelation is present in NGC 6388 (and to a smaller extent also in NGC 6441).

Although both clusters are affected by severe differential reddening, Piotto (2008) has been able to highlight the presence of two distinct SGB loci. No clues about a possible MS splitting have been collected owing to the limitations imposed by the reddening. On account of the close similarities between the two twin clusters, it is plausible that the same outcome could also apply to NGC 6441.

It is worth noting that the peculiar HB morphology of NGC 6388 (and NGC 6441) has been interpreted (Caloi & D'Antona, 2007; Busso et al., 2007) as due to the presence of multiple HB sub-populations characterised by distinct initial He contents, with some spread. How this scenario might be associated with the recent discovery of two SGB sub-populations is an issue that has not yet been addressed.

NGC 6121

Accurate spectroscopic data collected with FLAMES and UVES at the VLT have recently provided the evidence (Marino et al., 2008) that this cluster shows an extended Na-O anticorrelation, and that two distinct groups of stars with significantly different Na and O content are present. In addition, a tight correlation between the NaO and the CN abundances seems to exist. The coupling of the spectroscopic data with accurate photometric evidence has also shown that the two sub-populations with different Na abundances occupy distinct positions (have different colours) along the RGB when the *U*-band (likely influenced by *NH*- and *CN*-bands) is included (see Figure 4). However, due to the dependence of the result on the adopted photometric band, we caution that this empirical finding may not be a genuine proof of the presence in this cluster of distinct sub-populations. We note that the mass of this cluster is an order of magnitude smaller than that of any other GC hosting multi-populations.

A link with cluster properties?

It has already been noted that the five GCs that so far show evidence of the presence of multi-populations, are among the ten most massive clusters in the Galaxy. One may expect that the most massive clusters are more successful in retaining the nuclear-processed ejecta of a first generation of stars, from which a second (or further) stellar generation subsequently formed. However, one has also to note that NGC 1851 is not such a massive cluster, and the situation becomes even more puzzling when considering also the case of NGC 6121, which is a GC with a small mass. The only way to reconcile this discrepancy relies on the plausible assumption that the actual mass of many GCs is just a – sometimes minor – fraction of the initial total mass, as a consequence of tidal shocks with the Galactic disc.

It is also worth noting that almost all clusters hosting multi-populations are also characterised by a high central velocity dispersion. So one could be tempted

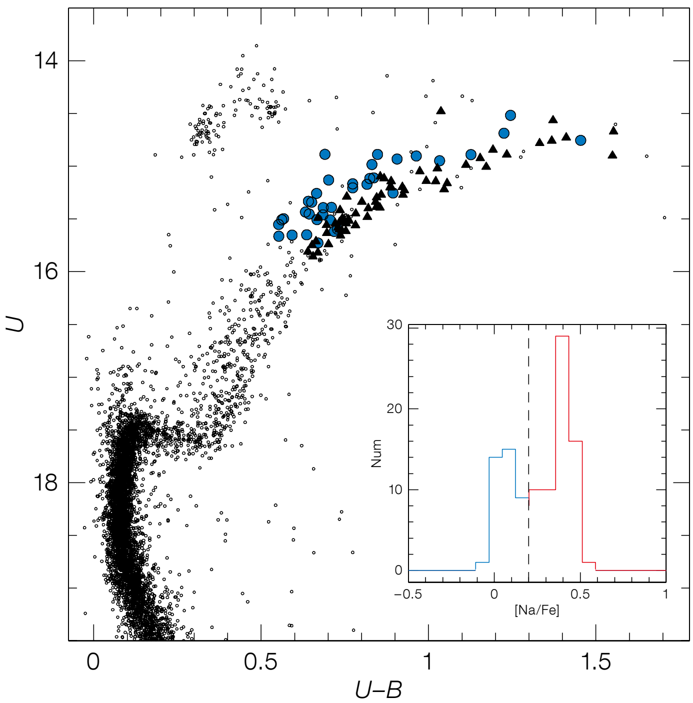

Figure 4. The colour-magnitude diagram of NGC 6121 and the distribution of Na abundance from Marino et al. (2008). The different colours identify the stars belonging to the two different Na groups.

to look for a link between the presence of multi-populations, a high total (initial?) mass and high central velocity dispersion. An interesting working hypothesis would be to associate multi-populations with the presence of an intermediate mass black hole (IMBH).

An observable fingerprint of the presence of an IMBH would be a small slope in the radial density distribution in the core region that would affect the surface brightness profile (Baumgardt et al., 2005; Trenti et al., 2007). Some empirical (Noyola et al., 2008) and theoretical (Miocchi, 2007) indications have been collected that seem to support this possibility.

The expected effects of the presence of an IMBH in the core region of a stellar cluster are: (1) the BH would act as a 'heat source' in the central regions; (2) it would strongly enhance the mass loss of RGB stars passing close by; (3) it could trigger multiple star formation bursts. It is evident that these processes – if really occurring – would allow many of the features observed in the GCs hosting multi-populations to be explained.

The observational framework is becoming more and more complex, but the new empirical findings are of pivotal importance to shed light on the formation and early evolution of GCs. Therefore, we are now on the right path to piecing the jigsaw puzzle together.

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Linking Chemical Signatures of Globular Clusters to Chemical Evolution

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The majority of Globular Clusters (GC) show chemical inhomogeneities in the composition of their stars, apparently attributable to a second stellar generation in which the forming gas is enriched by hot CNO-cycled material processed in stars belonging to a first stellar generation. We review the reasons why the site of the nucleosynthesis can be identified with hot-bottom burning in the envelopes of massive asymptotic giant branch (AGB) stars and super-AGB stars. The analysis of spectroscopic data and photometric signatures, such as the horizontal branch morphology, shows that the percentage of 'anomalous' stars is 50 % or more in most GCs examined so far. If anomalies are the rule and not the exception, then they clearly are closely related to the dynamical way in which GCs form and survive. We show a possible solution obtained by a hydrodynamical model followed by the N-body evolution of the two stellar populations, and propose that most GCs survive thanks to the formation of the second stellar generation.

The most massive AGB stars as sites of nucleosynthesis of CNO, ^{23}Na, ^{27}Al and ^{7}Li

The presence of the CN dichotomy, and of the Na-O and Mg-Al anticorrelations among the stars of practically all GCs examined in the Milky Way, show very clearly that the matter of 'anomalous' stars must have been processed through the hot CNO cycle, i.e. it has not only experienced CN, but also ON cycling. This process occurs deep in stellar interiors during the H-burning stage or at the 'hot' bottom of the convective envelopes of massive asymptotic giant branch stars. The so-called metals (iron, but also calcium and the other heavy elements) do not show significant star-to-star variations in most GCs (Gratton et al., 2004), so that any process of production of the anomalous gas does not involve supernova ejecta. Associated 'anomalies' include carbon depletion and nitrogen enhancement in a fraction of the cluster stars, and it has been shown that the increase in nitrogen is not only due to CN cycling, but must also include N production at the expense of oxygen (see, e.g., Cohen et al., 2002; 2005), thus relating the Na-O with the C-N anticorrelations.

If neither supernovae that are due to the core collapse of massive stars (SNe II), nor supernovae that occur much later in the life of the clusters (SNe Ia) had a role to play in the process of self-enrichment, the most obvious source is the massive AGB stars, as already proposed in the 1980s, notably by Cottrell & Da Costa (1981). The hot CNO-processed matter of the AGB envelopes is injected into the cluster at low velocity by stellar winds and planetary nebula ejection, and the stellar remnants are quiet massive white dwarfs (WDs). The very high temperatures at the bottom of the convective envelopes (T_{bce}) of these stars are exemplified in Figure 1, and no peculiar extra mixing needs be invoked to obtain the necessary very hot CNO processing. Hot-bottom burning (HBB) was recognised as an important physical process in these stars in the 1970s, and ^{3}He burning with ^{4}He, followed by the non-instantaneous mixing of the resulting ^{7}Be (Cameron-Fowler hypothesis) could explain the presence of abundant lithium, due to beryllium decay, in very high luminosity M giants that are above the highest luminosity limit for carbon stars. More recently, the possibility that the anomalous gas comes out from fast-rotating massive stars has been explored by the Geneva group (e.g., Decressin et al., 2007), but this model has not yet been fully explored from the dynamical point of view.

In some recent work, the AGB enrichment scenario, although appealing for the dynamical reasons quoted above, has often been considered inadequate to explain the features of the second stellar generation (SG). This is attributable to the fact that the results of stellar modelling of massive AGB stars obtained by different groups differ greatly from each other.

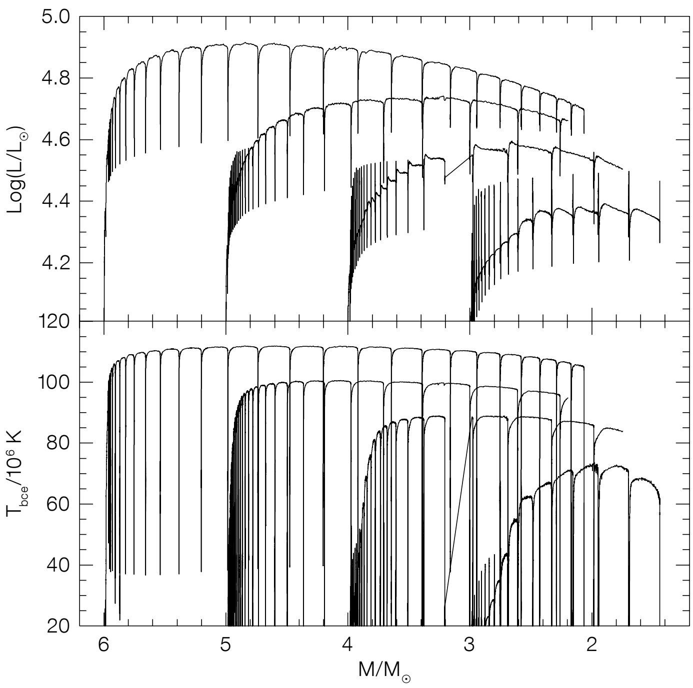

Figure 1. Luminosity (upper) and temperature at the bottom of the convective envelope T_{bce} (lower) in models of 6, 5, 4 and 3 $M_\odot$ with metallicity Z = 0.001. The abscissa is the current mass of the evolutionary track, which decreases due to mass loss (from the Ventura and D'Antona models). The very high T_{bce} values allow hot-bottom burning in all models down to 4 $M_\odot$, and only marginally in those of 3 $M_\odot$. More massive stars have faster nucleosynthesis and evolution, a smaller number of thermal pulses and third dredge-up episodes, so their evolution is able to account for the chemistry of the second generation stars.

The uncertainty in the nuclear cross-sections has often been emphasised in the work of, e.g., Lattanzio, Karakas, Izzard and Ventura. In particular, the very important sodium yield is made up by a series of events: it first increases in the envelope due to the second dredge-up (e.g., Iben & Renzini, 1983); then increases due to HBB of the ^{22}Ne dredged up in this same event; afterwards, it increases in the third dredge-up episodes. If T_{bce} is high, sodium is destroyed by p-captures. Notably, however, the ^{23}Na(p,α)^{20}Ne and, especially, the ^{22}Ne(p,γ)^{23}Na cross-sections are very uncertain in the range of temperatures of interest for HBB, by up to a factor 10^3 for the latter (compare Hale et al., 2002 with the 'standard' NACRE cross-sections found in Angulo et al., 1999). By choosing a high rate for this cross-section, the ^{23}Na yield of massive AGBs, where HBB is actively depleting oxygen, is high and compatible with the observations. Also the ^{27}Al production, by proton capture on ^{25}Mg, ^{26}Mg and ^{26}Al, is crucially dependent on the relevant cross-sections, and selection of the highest possible rates in the NACRE compilation allows the observed Mg-Al anticorrelation to be reproduced today.

The highest uncertainty in modelling is recognised to be the treatment of convection: the discrepancy, e.g., between the yields obtained by Karakas & Lattanzio (2007) and ours is mainly due to this modelling (Ventura & D'Antona, 2005). We adopt a very efficient convection model, proposed by Canuto et al. (1996), the Full Spectrum of Turbulence model, or FST. This results in a higher T_{bce} and more efficient nuclear processing, higher luminosities, higher mass-loss rates and consequently a lower number of third dredge-up episodes. Thus the oxygen reduction is not nullified by the third dredge-up, and the sodium is not increased too much by the dredge-up of ^{22}Ne (the ultimate product of ^{14}N burning in the helium intershell) and its consequent burning by p-captures.

Nevertheless, the sodium and oxygen yields in the matter expelled from AGB stars are directly correlated: lower initial masses, with smaller T_{bce}, longer AGB lifetimes and a higher number of third dredge-up episodes, have higher oxygen and sodium abundances. This is shown schematically in Figure 2: the three diagonal lines represent the Na and O yields (and their possible uncertainty) for AGBs as a function of the AGB mass, decreasing from left to right. It is clear that the anticorrelation shown by observations (dots) cannot be explained by the occurrence of star formation in pure matter expelled from AGBs of decreasing mass. The AGB matter must be diluted, at some level, with pristine matter, providing values of Na and O intermediate between the AGB starting yield and the pristine value. This is exemplified by the Na-O area within the cone drawn in the figure. The Na-O anticorrelation thus requires two events: (1) the minimum mass contributing to the SG should not have sodium abundance too high with respect to the observed values; (2) the AGB matter must be diluted with pristine gas.

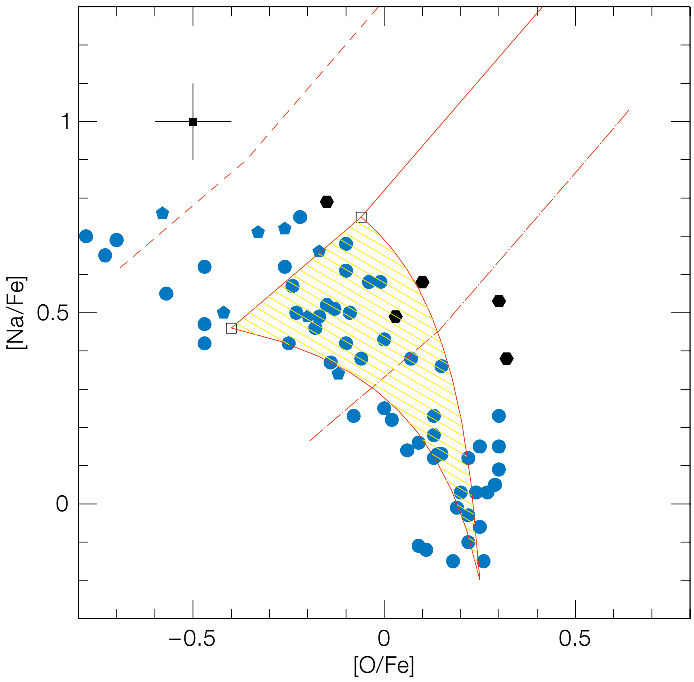

Figure 2. Schematic representation of the observed Na-O anticorrelation (dots). The diagonal lines represent schematic yields of AGB models, having decreasing mass from left to right. The middle line represents yields that can be consistent with observations; the lower line represents the yields obtained by adopting smaller cross-sections for the ^{22}Ne(p,γ)^{23}Na reaction and the highest line represents yields that can be obtained with a less efficient convection model. The dashed cone region includes abundances obtained by diluting the yields given by the two open squares, along the chosen yield line, with different amounts of pristine material having the composition of the cone vertex. It is evident that a satisfactory interpretation of the data requires such a dilution model, and cannot simply rely on the 'pure' abundances of the ejecta. In this scheme, the abundance points outside the cone (smaller O abundances, found only in red giants) require some extra-mixing process in order to be explained.

A related observational and modelling problem is that of the CNO total abundances. If they are constant among normal and anomalous stars, this implies that the AGB evolution must have suffered only a few episodes of third dredge-up. Or it might indeed imply that the matter is only CNO cycled, as can happen preferentially in the evolution of massive stars. The CNO data of Carretta (2005) seem to indicate a small, but unequivocal, overabundance of total CNO in the anomalous stars. This may favour the AGB scenario, indicating that a limited number of third dredge-up episodes actually play a (small) role. The most interesting indications in favour of the model came recently from the spectroscopic and photometric analysis of the cluster NGC 1851: this is the only cluster for which the total CNO variation may reach a factor ~ 4, as shown by Yong and collaborators in this meeting, and the giants also show an s-abundance spread, unlike all other GCs (Yong & Grundahl, 2008). Are we witnessing a GC in which the formation of the SG was slightly delayed with respect to the other clusters, so that it also involved the ejecta of AGBs suffering some more third dredge-up processing? The CNO total abundance variation in NGC 1851 is probably also related to the splitting of the subgiant branch and to its bimodal horizontal branch (HB) morphology, as presented in other reviews.

We finally touch on the problem of the lithium abundance of unevolved stars in GCs. In spite of the difficulties of observing this element in low luminosity turn-off stars, it has been known for many years that ^{7}Li in GCs varies from star to star, much more than observed in halo stars. In NGC 6752, Pasquini et al. (2005) have shown that lithium is anticorrelated with sodium. Na-normal, Li-normal stars do exist, as in the halo, and these should in fact be the first generation (FG) stars. Other stars then formed from mixing of the pristine matter with Na-rich, Li-poor material, thus providing the anticorrelation. But Pasquini et al. (2008) have recently shown that two stars in NGC 6397, both very similar and 'normal' in lithium, have oxygen abundances differing by ~ 0.6 dex. This may indicate that the O-poor matter is Li-rich too, and this is possible only if the SG forms from matter including AGB ejecta, and not massive star ejecta. The lithium yield of AGBs is extremely dependent on the mass-loss rates, but models providing yields close to the standard population II abundance are very reasonable.

Helium variations: super-AGBs as the site of production of extreme helium populations

All models of self-enrichment show that the ejected material must be enriched in helium with respect to the pristine one. The higher helium content has been recognised to have a strong effect on the HB morphology, possibly helping to explain some features (gaps, hot blue tails, second parameter) that have defied alternative explanation (D'Antona et al., 2002). A variety of problems along these lines have been examined in recent years: the extreme peculiarity of the HB in the massive cluster NGC 2808 (D'Antona & Caloi, 2004); the second parameter effect in M13 and M3 (Caloi & D'Antona, 2005); the peculiar features in the RR Lyrae variables; and the HB of the two metal-rich clusters NGC 6441 and NGC 6388 (Caloi & D'Antona, 2007; Busso et al., 2007). The presence of strongly enhanced helium in peculiar HB stars has been confirmed in NGC 2808 and NGC 6441 by spectroscopic observations (see, e.g., Moehler et al., 2004; 2007). In addition, an unexpected feature has recently appeared from photometric data, confirming the interpretation of helium differences amongst GC stars, *viz.* the splitting of the main sequence in NGC 2808. After first indications from a wider-than-expected colour distribution found by D'Antona et al. (2005) from archival Hubble Space Telescope (HST) data, recent HST observations by Piotto et al. (2007) leave no doubt that there are at least three different populations in this cluster. This finding came after the first discovery of a peculiar blue main sequence in ω Centauri by Bedin et al. (2004), also interpreted in terms of a very high helium content (Norris, 2004; Piotto et al., 2005). The above-mentioned cases can be considered as extreme, in the sense that no explanation had been attempted for them before the hypothesis of helium-enriched populations.

The helium yield of AGBs is in part due to the second dredge-up, in part to the effect of the third dredge-up episodes. As the number of these third dredge-ups must be small in order to preserve the quasi-constancy of CNO, the main effect must be due to the second dredge-up. While standard AGB models do not reach helium yields larger than Y ~ 0.35, and thus seem unable to explain the larger Y values of ω Centauri and NGC 2808, the super-AGB models by Siess (2007a) show yields Y ~ 0.36–0.38, and suggest these stars as candidates for the progeny of the extreme GC population.

Between the stars that evolve into core-collapse supernovae and the minimum mass for carbon ignition (below which stars evolve into CO white dwarfs), the super-AGB stars ignite carbon off-centre in semi-degenerate conditions, but are not able to ignite hydrostatic neon-burning in the resulting ONe core. Consequently, degeneracy increases in the core, and these stars may undergo thermal pulses, as first shown in models by Iben's group in the 1990s (e.g. Ritossa et al., 1999), and lose mass as 'normal' (but quite massive and luminous) AGB stars, but different in core composition (ONe versus CO) and core mass (> 1.05 $M_\odot$). Although full models through the super-AGB thermal pulse phase are not yet available, we can foresee that the sum of the CNO abundances can remain close to the initial value as a result of the efficiency of third dredge-up being limited, because the helium luminosity during the thermal pulses is weak, as shown again by Siess (2007b). These are the premises that make super-AGBs good candidates for the formation of the extreme helium population harboured in the most massive GCs (Pumo et al., 2008).

The fate of super-AGBs depends on the competition between mass-loss rate and core growth: if mass-loss wins, they evolve into massive ONe white dwarfs; if the core grows until it reaches the Chandrasekhar mass, they evolve into electron capture supernovae (ecSNe), electrons being captured on the Ne nuclei. Thus a fraction of the super-AGBs may explode as supernovae, but these events are at least a factor ten less energetic than the SNe II (≤ 10^{50} erg) and also a factor ten less frequent than SNe Ia. Consequently, the epoch during which super-AGBs evolve is probably the quietest period in the cluster lifetime, perturbed at most by ecSN explosions. This stage is not energetic enough to alter either the gas evolution or its chemistry, as the whole core remains locked by the remnant neutron stars. It has recently been proposed that practically all the neutron stars (NS) present today in GCs are born from ecSNe. Due to their lower energy output, it is also probable that the newborn NS receives a proportionally smaller natal kick, which allows it to remain bound to the cluster (Ivanova et al., 2008). If there are no energy sources (SN II or SN Ia) able to expel the gas ejected at low velocity by stars, this gas can collapse into the cluster core and form new stars with the chemistry of the ejecta.

What is the percentage of second generation stars?

We point out that helium variations produce appreciable differences in the location of the main sequence of clusters only if they are very large and *uniform* (D'Antona & Caloi, 2004; Salaris et al., 2006). Small helium spreads can be revealed from the HB morphology, which amplifies any small total mass decrease, by increasing the stellar T_{eff} location on the HB, but helium spread in the turn-off and main sequence stars remains hidden in the observational errors. Therefore, we should not regard the clusters with split main sequences (ω Centauri and NGC 2808) as typical examples of clusters with multiple stellar populations: they are examples of clusters also harbouring an extreme population identified by its blue main sequence, corresponding to Y ~ 0.38–0.40.

D'Antona & Caloi (2008) have examined the HB features of about 15 clusters and have shown in most cases that the higher helium abundances remain confined below Y ~ 0.32. Nevertheless, the percentage of SG stars – defined now as all stars with Y larger than the 'standard' Big Bang abundance Y ~ 0.24 – is generally larger than 50 %! D'Antona & Caloi (2008) also pose the question of whether GCs with only a blue HB (the classic second parameter effect) should be explained by assuming that these are clusters formed only from second generation stars. One of the interesting cases is NGC 6397, the small cluster with an HR diagram that has always been regarded as a perfect example of a simple stellar population, especially following the HST proper motion observations by King et al. (1998) and most recently by Richer et al. (2006). Nevertheless, only three scarcely evolved stars out of 14 are nitrogen normal (Carretta et al., 2005), leading us to suspect that the material from which most stars formed is CNO processed and thus belonging to the SG. This occurrence had already been noticed by Bonifacio et al. (2002), with reference to the paradox that nitrogen-rich stars had almost normal lithium content. The question remains whether NGC 6397 is an SG-only cluster.

We are finally confronted with the real question: how does a GC form? Is it possible to form a cluster with FG and SG stars in equal proportions? Is it possible to have a cluster made up only of SG stars? All GCs so far examined appear to contain an SG!

Is the second generation necessary for the survival of globular clusters?

A back-of-the-envelope computation is enough to realise that the matter forming the SG stars far exceeds the wind matter contained in massive AGBs, if the initial mass function (IMF) of the system is more or less standard and we assume that the FG low mass stars we see today represent the low mass end of the IMF. The initial population from which we need to collect AGB winds, massive enough to produce a populous SG, must have been at least a factor ten more massive than today's cluster mass. This requirement lends support to the idea that GCs are either the compact nuclei of dwarf galaxies (Bekki & Norris, 2006) or are formed within dwarf galaxies that are afterwards dispersed.

A different point of view is assumed in the recent work by D'Ercole et al. (2008): they start with a massive FG cluster, and follow the hydrodynamic formation of the SG. After the Type II supernova epoch, which cleared the cluster of its pristine gas, the low velocity winds of super-AGBs, and then of massive AGBs, collect in a cooling flow in the innermost regions of the cluster, where they form SG stars. The cluster emerging from the hydrodynamical simulations is one with an SG strongly concentrated at the inner core of a more extended FG population. The initial mass of the FG stars needs to be large enough to provide enough stellar mass return and to form a substantial number of SG stars. Consequently, the FG stars are initially the dominant stellar population with a total mass that must be about ten times larger than the total mass of the SG stars. The SG formation ends when SNe Ia begin to explode regularly in the cluster. As SN Ia explosions occur when CO WDs reach the Chandrasekhar mass by accretion in binary systems, this epoch certainly begins some time after the birth of massive CO WDs, so that both super-AGBs and the most massive AGBs can contribute to the cooling flow, consistent with the scenario outlined above. In 100 Myr (at most) a cluster with two dynamically separated components has been formed.

The dynamical evolution of the composite FG plus SG cluster is followed by means of N-body simulations, starting with a highly concentrated SG, and an FG extended to the tidal radius. The FG is also expanding, due to the SN II explosions and consequent mass loss. If the initial FG was already mass-segregated (as massive clusters seem to be observationally), the heating and the expansion due to the loss of SN ejecta are augmented by the preferential removal of the mass from the inner regions of the cluster. D'Ercole et al. (2008) find that early cluster evolution and mass loss can lead to a significant loss of FG stars. In Figure 3 we show that the number ratio of SG to FG stars (f_{MS}) may not only reach values consistent with observations (0.5–1.5), but that there may also be evolutionary routes leading to the loss of most of the FG population and leaving an SG-dominated cluster. Thus this model shows that the clusters that survive might preferentially be those in which a substantial SG has had time to form.

Back to the helium inhomogeneity

We have seen that, from the chemical point of view, the less extreme anomalies require mixing of the AGB ejecta with pristine gas in order to be explained. On the contrary, the dynamical model described above is based on the fact that the SNe II have fully cleared the cluster of its pristine gas. A way to solve this problem has been approached in the model by D'Ercole et al. (2008): if the SNe have a preferential direction of ejection, the ejected matter clears out a cone, and leaves a torus of pristine gas in the outskirts of the cluster within the tidal radius. This pristine gas may be re-accreted (in fact the hydro simulation shows that it is re-accreted) and mixes with the AGB ejecta, providing the desired solution. The model provides us with a very simple solution to the problem of the three separate helium populations in NGC 2808. In the most massive clusters, the super-AGB winds are the first to be collected in the cluster core, and the first SG stars are formed by 'pure' super-AGB ejecta, and with a homogeneous, very high, helium content as the observations require. After a while, not only have the ejecta a smaller helium content, since they come from less massive AGBs, but they also become diluted by the pristine matter at standard helium Y ~ 0.24. A result of such a simulation, obtained without any tuning of parameters, is shown in Figure 4, compared with the helium distribution inferred for the stars in NGC 2808 (D'Antona & Caloi, 2008).

Much more will no doubt be learnt about GC formation in the near future, but at least one of the most difficult problems – the mass budget and the loss of the FG stars – might be on the verge of being fully understood.

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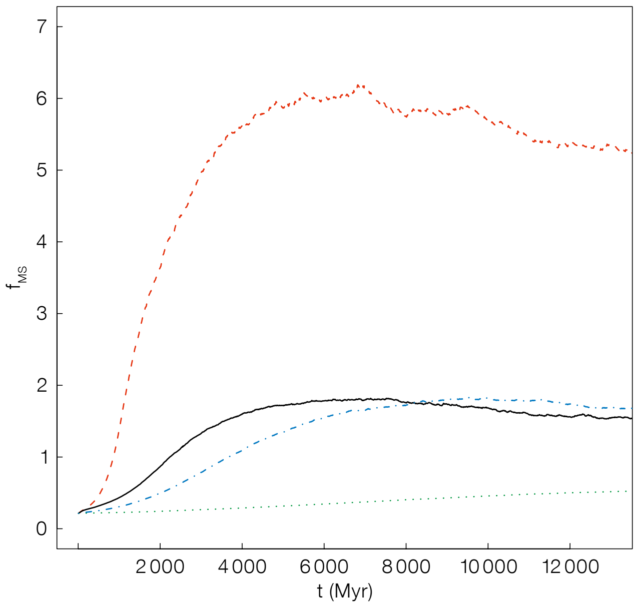
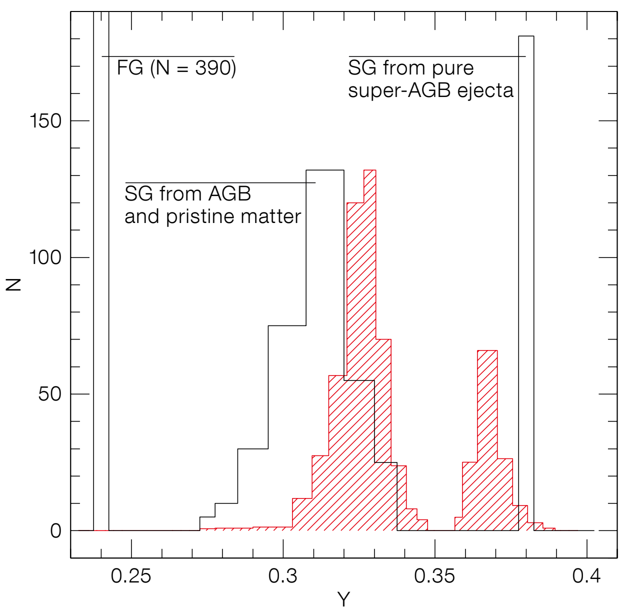


Figure 3 (above). Time evolution of the ratio of the number of second generation (SG) to first generation (FG) main sequence stars with $0.1 < M/M_\odot < 0.8$, f_{MS}, for different N-body simulations (D'Ercole et al., 2008). Depending on the initial expansion velocity assumed for the FG (due to the mass loss of SNe II that are more or less concentrated in the cluster core), the SG could even become the dominant cluster population.

Figure 4 (below). The empty histogram represents the number versus helium content distribution (N(Y)) for stars in NGC 2808, derived by D'Antona & Caloi (2008) on the basis of the features of the horizontal branch and main sequence. Three distinct populations are present. The hatched red histogram represents the second generation (SG) formation in a dynamical model in which it is assumed that some pristine gas of the first generation (FG) is in a torus at the periphery of the cluster following the SN II epoch. In this model there is a first phase of SG formation in the core of the cluster when only the super-AGB winds are present, followed by a phase during which the winds are diluted by pristine matter being re-accreted again. This two-phase pattern produces a gap in the N(Y) distribution. No attempt has been made here to fit the two SG populations to the data (adapted from D'Ercole et al., 2008).



Chemical Signatures in Dwarf Galaxies

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Chemical signatures in dwarf galaxies describe the examination of specific elemental abundance ratios to investigate the formation and evolution of dwarf galaxies, particularly when compared with the variety of stellar populations in the Galaxy. Abundance ratios can come from H II region emission lines, planetary nebulae, or supernova remnants, but mostly they come from stars. Since stars can live a very long time, for example, a 0.8 $M_\odot$ star born at the time of the Big Bang would only now be ascending the red giant branch, and, if, for the most part, its quiescent main sequence lifetime had been un-eventful, then it is possible that the surface chemistry of stars actually still resembles their natal chemistry. Detailed abundances of stars in dwarf galaxies can be used to reconstruct their chemical evolution, which we now find to be distinct from any other component of the Galaxy, questioning the assertion that dwarf galaxies like these built up the Galaxy. Potential solutions to reconciling dwarf galaxy abundances and Galaxy formation models include the timescale for significant merging and the possibility for uncovering different stellar populations in the new ultra-faint dwarfs.

The Local Group

The Local Group seems to be more crowded now than it was ten years ago. Although we knew about the three large spiral galaxies (the Milky Way – hereafter MWG, M31, and M33), and we knew about dwarf galaxies with smaller masses (the Magellanic Clouds and other smaller satellites of the MWG and M31, as well as the isolated dwarfs), what we did not know was that there were also extremely faint and low mass dwarf galaxies lurking within our midst. These galaxies, mostly discovered in the Sloan Digital Sky Survey (SDSS; e.g., Belokurov et al., 2007) data, have properties that are only now being uncovered (see presentations at *http://www.mpa-garching.mpg.de/mpa/conferences/garcon08*).

How these different types of galaxies are related to one another raises an interesting series of questions. Are dwarf galaxies related to protogalactic fragments, the low mass systems that formed in a Λ Cold Dark Matter (LCDM) Universe that later merged to build up the large spirals that we see today? Are the dwarf spheroidal and Sloan galaxies that we find in the halo of the MWG related to the gas-rich dwarf irregular and gas-poor transition galaxies that are further away and often isolated? One way to address these questions is to search for similarities in the chemical patterns of the stars in these galaxies.

The build-up of the chemical elements is unique to each galaxy, depending on their mass, initial conditions, star formation histories and gas infall and outflow properties. Since dwarf galaxies do not exchange gas with one another (other than through major merging events that leave only one galaxy remaining), then the chemical evolution of each dwarf galaxy is independent. So how does the chemistry in each dwarf galaxy differ, or are they all the same? Looking at the stars in the MWG suggests that they are not all going to be the same.

Chemical signatures: from the Milky Way to Local Group (dwarf) galaxies

The first studies of the chemical evolution of the stars in a galaxy occurred in the 1970s by Beatrice Tinsley and collaborators (e.g., Tinsley, 1979). In these studies, they collected the detailed elemental abundances in metal-poor stars in the Galaxy and tried to model the build-up of the elements to the present day, assuming that the Galaxy formed from a monolithic collapse (Eggen, Lynden-Bell & Sandage, 1962). The achievements of these early models are impressive. Looking at Figures 3 and 6 from Tinsley (1979), an examination of the rise in s-process elements through the evolution of asymptotic giant branch (AGB) stars is not too different from the results of today's more sophisticated (and physically accurate) models.

Studies of the chemical abundances of stars in dwarf galaxies are more recent. Shetrone et al. (1998) determined the first detailed chemistries for stars in the Draco dwarf galaxy. Ironically, they were mainly interested in using the stars in Draco to address the pattern of deep mixing that is seen in red giant stars in globular clusters, but never in similar field stars in the Galaxy, but quickly realised the potential of this work for examining galaxy formation. Previous to Shetrone's work, elemental abundances were determined only for H II regions, planetary nebulae, and bright supergiants in the Magellanic Clouds (e.g., Olszewski et al., 1996). This can tell us about the end point of the chemical evolution of these galaxies, but not of the initial conditions, nor the intervening steps, because all of these objects are young. Some carbon abundances had been determined for stars in the Ursa Minor dwarf galaxy (Suntzeff, 1985), but no other elements were examined. It is impressive that we have gone from four lone stars in one dwarf galaxy to hundreds of stars in five dwarf galaxies in less than a decade, and with more stars and galaxies on the way.

We are into the decade of large samples of stars in other galaxies with detailed chemical abundance determinations. These datasets allow us to: (1) characterise a wider variety of stellar populations; (2) examine similarities and differences with respect to MWG stellar populations, as well as between the various dwarf galaxies; (3) constrain nucleosynthesis and stellar yields in the models; (4) examine supernova (SN) feedback and reionisation effects on the evolution of dwarf galaxies; (5) disentangle age and metallicity effects in the analysis of the red giant branch from colour-magnitude diagrams – which can still be a complicated procedure; and (6) couple metallicity and kinematic information to examine variations in time and location of star formation events, and/or galaxy interactions. Ultimately, all of these individual questions are important in making comparisons with the MWG stellar populations, testing galaxy formation scenarios and LCDM cosmology.

Chemical signatures in the Milky Way

There are five dwarf galaxies to date with detailed chemistries determined for a large sample of stars. These include the three dwarf spheroidal galaxies (Sculptor, Fornax and Carina), as well as two dwarf irregular galaxies (LMC and Sagittarius). Most of these abundance analyses have been from high resolution spectra taken at the VLT with the FLAMES and UVES spectrographs. Examination of the colour-magnitude diagrams for these five galaxies show that each has had a very different star formation history (e.g., Tolstoy et al., 2003; Smecker-Hane et al., 2002; Bellazzini et al., 2006). The simplest assumption is that they have had very different chemical evolution routes from one another as well. But, do any of them have a chemical history similar to any of the stellar populations in the Galaxy (e.g., halo, thin disc, retrograde stars, etc.)?

All the chemical elements are of interest in this examination, though some give more information than others. α-elements are particularly important when compared with iron group elements, because they have different nucleosynthetic sources: iron forms during the surface detonation of a white dwarf in a Type Ia supernova explosion; α-elements are those that form through α-captures during nucleosynthesis (i.e., the capture of a helium nucleus, e.g., oxygen, magnesium, silicon, calcium, during quiescent helium burning in the core of massive stars). Thus the alpha/iron ratio is similar to examining the yields from hydrostatic burning in massive stars versus those from explosive nucleosynthesis in low mass stars. Differences in the star formation history of a galaxy will show up as differences in the alpha/iron ratios.

Of course, the simplest interpretation of the alpha/iron ratios in stars can be complicated by SN feedback, gas infall, or other events in the evolution of a galaxy. Thankfully these additional processes can have a different influence on the abundances of other elements. Other elements worth examining include r-process elements (i.e., those that form through rapid neutron capture during Type II supernova collapse, e.g., europium, neodymium, gallium) and s-process elements (i.e., those that form through slow neutron capture during the thermal pulsing phases of an AGB star, e.g., yttrium, strontium, barium). The reason that the s-process and r-process elements are particularly useful is not only their different nucleosynthetic sites and timescales for enrichment, but also that the yields from these sites are metallicity dependent. Their dependence on metallicity (the seeds for these processes) makes the build up of these elements strongly coupled to the star formation history of the host galaxy, which builds up over a non-unique timescale. Thus, variations in star formation history, as well as variations in SN feedback or gas infall/outflow, can be probed with s-process/r-process element ratios and alpha/r-process ratios.

In Figure 1, the abundances of calcium (α-element) and barium (r-process and s-process element) are compared to iron for stars in the Galaxy, as compiled by Venn et al. (2004). The element patterns for these two elements are not the same. When the iron abundance is quite low, then the calcium abundance does not quite scale in the same way, such that there appears to be an overabundance of calcium relative to the iron deficiency. Barium, however, is even more deficient than iron at low metallicities. These ratios are plotted with respect to the Sun (which is at [Fe/H] = 0, and on a logarithmic scale). Why do these elements have different patterns?

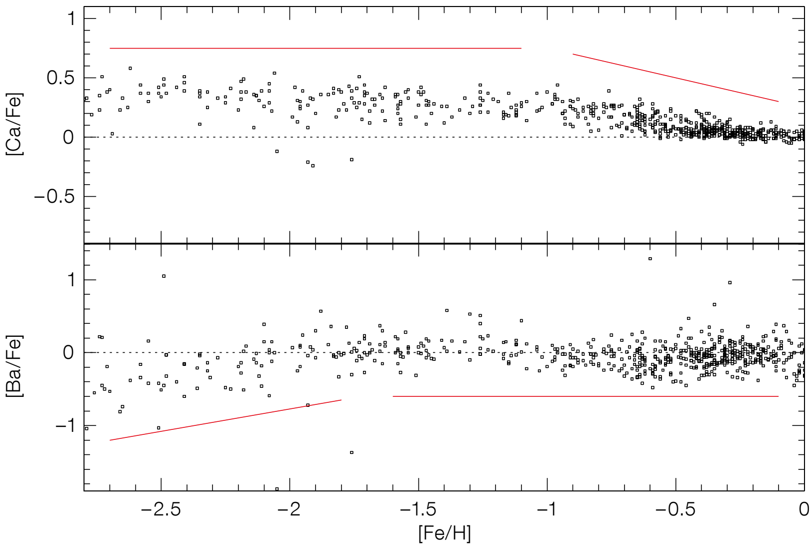

Figure 1. Comparison of the change in the calcium and barium abundances relative to changes in the iron abundances of stars in the Galaxy. The long red lines are a guide to the yields of these elements during the chemical evolution of the Galaxy. For [Ca/Fe] the high values at low [Fe/H] represent the yields from massive star nucleosynthesis and Type II supernovae, while the downward slope after [Fe/H] = –1.0 represents the contribution only to iron from low mass Type Ia supernovae. For [Ba/Fe], the rising line at low [Fe/H] values represents the increasing yield of barium over iron from Type II supernovae of higher metallicity, while the flat line after [Fe/H] = –1.8 represents the coincidentally similar yields of barium, from intermediate mass AGB stars, and iron, from low mass Type Ia supernovae.

Calcium, as an α-element, forms in massive stars. The high calcium/iron ratio at low metallicities suggests that massive stars form both calcium and iron and deposit these elements back into the interstellar medium with the ratio seen on the plot. Eventually the low mass stars also evolve and explode as Type Ia supernovae. These events create iron-group elements without any calcium, causing the calcium/iron ratio to decrease (forming a 'knee' in Figure 1). Taken together, the suggestion is that the Galaxy was enriched to a metallicity 1/10th solar ([Fe/H] = –1.0; location of the knee) by massive stars alone, therefore rather quickly since massive stars have very short lifetimes (< 1 Gyr), and after this time the lower mass stars were able to contribute iron. This also means that the metallicity scale along the x-axis in Figure 1 is absolutely not linearly related to age! The first Gyr of our Galaxy's chemical evolution is represented by most of the figure, and the past 12 Gyr by a tiny portion on the righthand side.

Barium is an element that has contributions from both massive stars during Type II supernovae and rapid neutron capture, as well as intermediate mass stars during slow neutron capture happening in the AGB phase. That the barium/iron ratio rises at the lowest metallicities shows that Type II supernovae contribute less barium than iron, however as iron goes up, then more barium is made and the contribution of barium increases. At a metallicity near 1/50th solar ([Fe/H] = –1.8) then the barium/iron ratio is flat, implying that the yields of these elements are the same, but from what source? In the Galaxy, it appears to be a coincidence that the barium yield from the s-process in the AGB stars is similar to the iron yield from Type Ia supernovae (which contribute the iron at this metallicity).

Additionally, the position of the knee in the barium plot differs from that of the calcium plot in Figure 1 ([Fe/H] = –1.8 for barium/iron, rather than –1.0 for calcium/iron). Since AGB stars can include higher mass stars than Type Ia supernovae, then these stars will evolve and contribute their products at earlier times (or lower metallicities).

Chemical signatures in dwarf galaxies

How do these abundance ratios, discussed in the MWG context, look in dwarf galaxies? Are they the same as in the MWG? We might expect the ratios to be the same if the MWG formed from ongoing merging of small dwarf galaxies to the present epoch. The past decade of work on the chemistry of stars in nearby dwarf galaxies has shown that this is not the case, and that dwarf galaxies have their own unique chemical patterns and chemical signatures.

In Figure 2, the calcium and barium abundances are shown in the five dwarf galaxies that have had their chemistries determined from large samples of stars. The LMC stars analysed by Pompéia et al. (2008; red) show lower calcium and higher barium abundances than similar metallicity stars in the Galaxy. Thus, the stars in the Galaxy do not resemble those in the LMC. The stars in the Galaxy sample are from the thick and thin disc, and it had been proposed that the discs of our Galaxy could have formed through the merger of an LMC-sized dwarf galaxy (e.g., Abadi et al., 2003). However, if that were true then the chemistry of this virtual galaxy must have been quite different from that of the LMC itself.

Chemical abundances for the Sagittarius (Sgr) and Fornax dwarf galaxies from Sbordone et al. (2007; cyan points in Figure 2), Letarte et al. (2007; blue filled circles; 2006; blue open squares) and also a few stars from Shetrone et al. (2003; blue open symbols) are also unlike the stars in the MWG. Both also show lower calcium and higher barium than Galactic stars, though Sgr probes stars at higher metallicities than the LMC, while Fornax samples stars at slightly lower metallicities. Sgr and Fornax have had similar masses to the LMC, but the fact that their chemical abundance ratios differ from one another and those of the LMC suggests that other processes have been important, and that the mass of a dwarf galaxy alone does not fully determine its chemical evolution.

The Sculptor dwarf galaxy has a lower mass than the LMC, which is reflected in the lower metallicity of the majority of its stars as determined by Hill et al. (2008; green points in Figure 2), with a few stars from Shetrone et al. (2003) and Geisler et al. (2005) – green open symbols. While the calcium abundances are lower than in the Galaxy at intermediate metallicities, they are quite similar to those of the very metal-poor Galactic stars, overlapping the Galactic stars near [Fe/H] = –1.8. The barium abundances are not significantly different from Galactic stars. These imply some similarities in the early chemical evolution of the stars in the Sculptor dwarf galaxy to the MWG halo stars, however it also shows the power of having more than one element to examine. While there are similarities in the most metal-poor stars, variations in star formation histories, gas infall rates, or supernova feedback yields have affected the α-element abundances (calcium) at the time when the galaxy had reached intermediate metallicities. These results are similar to a sample of stars analysed by Koch et al. (2008; magenta points in Figure 2) in the low mass Carina dwarf galaxy.

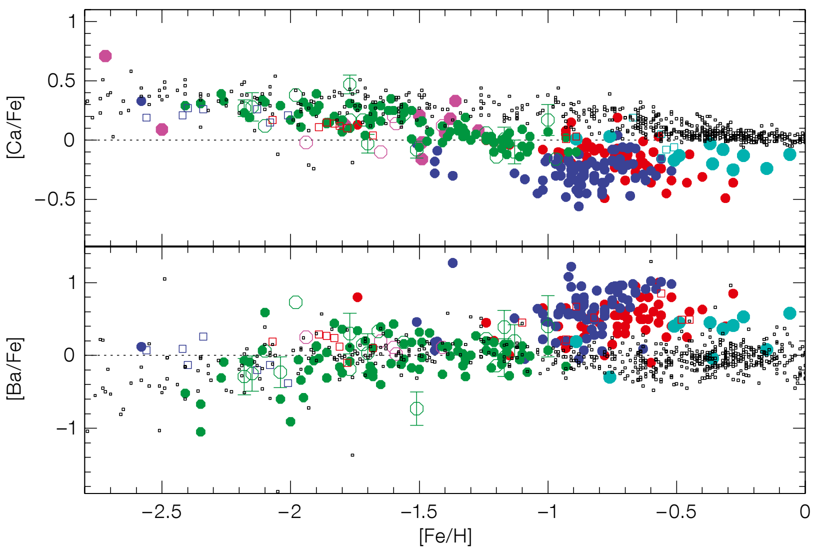

Figure 2. Calcium and barium abundances for stars in the dwarf satellites of the Galaxy, including the LMC (red), Sgr (cyan), Fornax (blue), Sculptor (green) and Carina (magenta). Open and closed circles are for field stars, open squares are results from stars in globular clusters in the dwarf galaxies. Representative error bars are shown for some stars in Sculptor. Clearly each dwarf galaxy has had a different chemical evolution from the others and from the stellar populations in the Galaxy. This effect can be seen in the [Ca/Fe] plot by a variation in the metallicity when Type Ia supernovae start to contribute iron (the knee where the ratio slopes downwards), and in the [Ba/Fe] plot where the yields of s-process barium are higher from the AGB stars (the high values occurring at high metallicities).

Interpreting chemical signatures in dwarf galaxies

The most impressive result from the calcium/iron and barium/iron ratios in Figure 2 is simply that each dwarf galaxy has its own chemical evolution. This was expected since each has its own unique colour-magnitude diagram, indicating significantly different star formation histories (SFH). Precise interpretation of effects of the SFH versus other chemical evolution parameters is complicated (see further discussion below). At the very least, we can see that the dwarfs with higher luminosities (and presumably masses) that have had more ongoing star formation, as reflected in the distribution of stars in their colour-magnitude diagrams, do have more stars at higher metallicities (e.g., the LMC versus Sculptor). While metallicity does not have to scale with mass, it is reasonable to expect that galaxies with more baryons will be able to form more stars over time, and therefore build up their metallicities to higher levels than those with less gas.

The two abundance ratios examined in Figures 1 and 2 tell us that the build up of these elements has occurred differently in each galaxy as well, e.g., new contributions from lower mass stars happened at different *metallicities* in each galaxy (we cannot say at different ages, because there is no universal age-metallicity relationship). This can be seen in the different positions of the knee for each element and in each galaxy. The knees themselves are difficult to see precisely because they occur at metallicities that were not well sampled in all of the dwarf galaxies, other than Sculptor. Examining only the calcium/iron ratio shows that the *most metal-poor* stars in each galaxy have similar alpha/iron ratios to the metal-poor stars in the Galaxy, however, at intermediate and high metallicities then the alpha/iron ratios are lower by varying degrees. Thus, the contribution to iron from low mass stars occurs at a different *metallicity* in each galaxy; in Sculptor, it occurs near [Fe/H] = –1.8, in Fornax and the LMC it occurs before [Fe/H] = –1.5, but we do not have data on a sufficient number of stars below that metallicity to be more certain. However, looking at the slopes of the calcium/iron ratios suggests that the LMC knee could be at the same metallicity as that for Sculptor (in spite of their significantly different masses and SFHs), whereas that for Fornax is at a lower metallicity, [Fe/H] ~ –2.0. The Sgr remnant is not well sampled at low metallicities, but examination of the slope suggests that the knee occurs at higher metallicity than in Sculptor, [Fe/H] ~ –1.0. The current data for Carina has too large a scatter to say much about the metallicity at which low mass stars began to contribute iron; this could be due to differences in the abundance analysis compared to the other analyses which were done more homogeneously, or it could be astrophysical and reflect a true and very large scatter in the Carina abundances due to its complex SFH. More data on this galaxy would certainly be interesting. Looking at the knee in the barium/iron ratios is similarly interesting.

Each galaxy has similar barium/iron ratios at the low metallicities sampled, which suggests similar r-process yields with the exception of Fornax, which may have had a higher r-process contribution (or retention of r-process elements from Type II supernovae). However, the barium/iron ratios are certainly higher in Fornax, the LMC and the Sgr remnant at higher metallicities, [Fe/H] > –1.0, when the barium abundance is mainly due to s-process contributions from AGB stars. This pattern is not seen in the Galaxy, nor the Sculptor dwarf galaxy. AGB yields are metallicity dependent – at lower metallicities, there are fewer iron seeds for slow neutron capture, thus first s-process peak abundances (such as yttrium) are sacrificed for the second and third s-process peak abundances (such as barium and lead), e.g., Travaglio et al. (2004); thus the higher barium/iron abundances suggest that lower metallicity AGB stars contributed to these higher s-process yields and that iron is primarily from the lower mass stars. We also note that these three galaxies have had more vigorous star formation rates at recent times (< 5 Gyr), thus the combination of their SFHs and chemical evolution has affected their recent AGB yields.

Chemical evolution models for the Sculptor galaxy have been published by Fenner et al. (2006) and Lanfranchi et al. (2006) with similar results to one another. One of the most interesting results from the Fenner et al. analysis was the degeneracy in the alpha/iron ratios between SFH and supernova feedback (see their Figure 2); the same pattern in alpha/iron ratios is possible no matter how different the star formation histories (they examined a SFH that ends at the moment of reionisation compared with a SFH that continues to intermediate ages, see their Figure 1), so long as the supernova feedback is adjusted to the data. This brings into question the value of the alpha/iron ratio as an indicator of chemical evolution! Fortunately, the heavy elements are not degenerate in these two parameters; when the supernova feedback is adjusted to fit the alpha/iron data, then the barium/iron ratio predictions are not the same. This shows the power and necessity of having many different chemical elements available for chemical evolution modelling of real systems. While their model with the continuous SFH fits the data from Shetrone et al. (2003) better than their other models, the larger sample size that we now have from Hill et al. (2008) no longer fits that model. Lanfranchi et al. (2008) have examined the chemical evolution of the heavy element abundances in six dwarf galaxies, including Sculptor, Carina and the Sgr remnant, yet did not predict the increasing abundances at high metallicities seen in Figure 2. New chemical evolution modelling of the Sculptor and other dwarf galaxies are now necessary.

New modelling of dwarf galaxies is being carried out (e.g., Jablonka, this conference). Marcolini et al. (2008) have used a 3D hydrodynamical simulation to examine the chemical properties of the inner regions of dwarf galaxies. They find that the stars in the inner region are relatively iron-rich and alpha-poor (as observed), but the 3D aspects of the models show that this pattern differs from the outer regions and also that the kinematics of the outer regions are hotter (as observed by e.g., Battaglia et al., 2006). This model does not currently examine the heavy elements.

Chemical comparisons between the dwarf galaxies and the MWG

Only the metal-poor Galactic halo has any chemical signatures in common with the dwarf galaxies; at the lowest metallicities in these systems, the alpha/iron and heavy/iron abundances are in good agreement (with the possible exception of Fornax where the r-process barium/iron ratios may be higher; see Figure 2). If this is true, then it appears that the earliest stages of star formation yield similar results in all systems and/or that the metal-poor halo of the Galaxy built up from the accretion of small dwarf galaxies at the earliest epochs, before the dwarf galaxies had any significant chemical evolution of their own.

Another way to test this proposition is from the shape of the metallicity distribution function (MDF) of the most metal-poor stars. Helmi et al. (2006) compared the metal-poor tails of the MDFs of the Galaxy and four dwarf spheroidal galaxies, but found the dwarf galaxies all have similar and sharper declining tails (their Figure 3). The conclusion was that the metal-poor Galactic halo could not come from the accretion of dwarf spheroidal galaxies. There are three other possible interpretations. Schoerck et al. (2008) have rescaled the Galactic MDF for a minor observational bias and selection function of the Hamburg/ESO Survey sample and suggest that the new Galactic MDF has a sharper metal-poor tail, in good agreement with the dwarf spheroidal galaxies. The rescaled MDF is normalised and compared to the dwarf galaxies at [Fe/H] = −2.0, a value that may be too high since significant chemical evolution can occur in the dwarfs by the time this metallicity is reached. However normalising and comparing the MDF at [Fe/H] = −2.5, as was done by Helmi et al. (2006) has a less significant effect on the original MDF and thus improves the comparison with the dwarfs, but still does not eliminate the inconsistencies. The second option relies on the contribution of the newly discovered ultra-faint dwarf galaxies (e.g., Belokurov et al., 2007). The majority of the stars in these galaxies are more metal-poor than the majority of stars examined in the other dwarf galaxies (e.g., Simon & Geha, 2007; Kirby et al., 2008). Characterising these galaxies and examining their MDFs could provide a missing link in our current testing of the hierarchical accretion of small systems in the early stages of galaxy formation.

The third option for the difference in the MDF between the well-studied dwarf spheroidal galaxies and the MWG is the unknown characteristics of the old stellar populations in the isolated dwarf irregular galaxies. Although these galaxies are more luminous, contain gas and have current star formation, their old populations have been unexplored chemically because of their distance and thus the faintness of their red giant stars. The only detailed analyses from calcium triplet spectroscopy of red giants in a dwarf irregular galaxy include ~ 20 stars in NGC 6822 (Tolstoy et al., 2001) and ~ 80 stars in the Wolf-Lundmark-Melotte Galaxy (WLM; Leaman et al., 2008). The analysis of the stars in WLM included 13 old stars, which is a very small number, but enough to suggest that the old population may have spheroidal kinematics unlike the younger populations or the H I gas that is rotationally supported.

The calcium triplet data for the red giants in NGC 6822 did not include stars with old ages (from isochrones), however similar work on the carbon stars (AGB stars with intermediate ages) by Demers et al. (2006) has come to the same conclusion, that the young stars have disc-like kinematics, but not the AGB stars which have spheroidal kinematics. Even the H I disc is peculiar in NGC 6822; de Blok & Walter (2000) have shown there is a hole in the H I distribution on one side of the disc and an apparent overdensity on the other side (which they suggest could be the core of a recently merged dwarf). Could all of the dwarf irregular galaxies really be dwarf spheroidal galaxies that have had a recent merger with a gas-rich system (or even just an H I filament), where the gas is in the orbital plane of the merger? Simulations by Brook et al. (2007) do suggest that polar ring galaxies could be a natural and common occurrence in the evolution of the dwarf galaxies. It is exciting that this is a testable prediction through examination of the metallicities and kinematics of the Local Group dwarf irregular galaxies, and that these galaxies, since they formed and evolved in relative isolation, could be different to the dwarf spheroidals and provide new information on the nature of unperturbed dwarfs at early epochs.

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Chemical Evolution of Dwarf Galaxies and Stellar Clusters: Conference Summary

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The summary begins by considering the contributions on the differences between globular clusters (GCs) and dwarf spheroidal (dSph) galaxies. Then I discuss globular clusters: the topics include multiple sequences in the colour-magnitude plane, light element abundance anomalies, globular cluster systems and other issues. The next section is devoted to dwarf galaxies, summarising new results on their kinematics, masses and baryon content, their star formation histories, and their chemical abundance ranges and chemical signatures. The last section discusses some of the other interesting related points that came up during the meeting.

Differences between globular clusters and dwarf spheroidal galaxies

We can summarise the important differences between GCs and dSph galaxies as follows:

- dSph galaxies overlap with GCs in absolute magnitude (M_V), but they have much lower stellar surface densities, larger half-light radii (r_h) and are more elliptical in shape. In the (M_V, r_h) plane, the classical globular clusters and dSph galaxies are well separated, although some of the recently discovered fuzzy GCs fall in the gap.
- dSph galaxies have a wide range of star formation histories, while the stars in GCs are more nearly coeval.
- dSph galaxies have a variety of chemical signatures, as seen most clearly in their wide range of stellar α-element abundances [α/Fe] as a function of [Fe/H] within individual dSph galaxies. In contrast, most GCs have a relatively tight and homogeneous distribution of stellar abundances.
- dSph galaxies are now found to follow a fairly tight abundance-luminosity relation, extending down to the least luminous of the newly discovered systems. This abundance-luminosity relation is shared by the dwarf irregular galaxies (dIrr), dSph and transition objects, despite their wide range of star formation histories and Galactic locations. The present low star formation rates in the star-forming dSph and dIrr galaxies may contribute to their similar abundance-luminosity relations. In contrast, globular clusters do not show such a relation. This important discovery indicates that the dSph galaxies make their own heavier elements during their (mostly) extended star formation histories, while the GCs primarily inherit their heavier elements from the gas out of which they formed. The tight relation between the stellar luminosity of dSph galaxies and their chemical abundance also suggests that tidal stripping of stars at later times may not be important for determining the low stellar luminosities of the fainter dSph galaxies: for example, dSph galaxies with low [Fe/H] and low stellar luminosities today probably did not have significantly higher stellar masses in the past.
- dSph galaxies have a range of M/L ratios extending up to very large values, indicating that most of their mass is in the form of dark matter. Globular clusters have low M/L ratios and appear to be baryonic.
- dSph galaxies have low baryonic densities and their associated stellar relaxation times are greater than a Hubble time. For most globular clusters, the relaxation times are shorter than a Hubble time.

There are clear environmental effects on the incidence of the nearby dwarf galaxies and GCs as a function of Galactocentric radius R_g. The inner halo (R_g < 30 kpc) is inhabited mainly by globular clusters. Then, out to R_g = 100 kpc, most of the satellite systems are dSph galaxies with primarily old stellar populations. Going out further to R_g = 300 kpc, the dSph galaxies have mostly extended star formation histories. Even further out, dwarf irregular galaxies dominate the satellite population, presumably due to some kind of interaction of the satellites with the parent galaxy.

We still do not know much about how the dSph galaxies and GCs fit into the overall picture of galaxy formation and evolution. The nature of the progenitors of today's dSph galaxies is not understood. They are probably not like today's dwarf irregular galaxies, although rotation has recently been discovered for the first time in a dSph galaxy (Scl). The globular clusters are unlike any of the known clusters that are currently forming stars within the Galaxy. Some of the younger clusters in the Large Magellanic Cloud (LMC) and other galaxies are, however, very similar in mass and structure to the old Galactic GCs. We do not yet understand the conditions that are needed to form the globular clusters.

Globular clusters

Multiple populations

Several of the (mainly) more luminous Galactic GCs show multiple sequences in their colour-magnitude distributions. In ω Centauri, five giant branches and two main sequences are seen. The bluer main sequence is more metal-rich, its stars are more centrally concentrated in the cluster, and it is believed to be He-rich, with Y ~ 0.4. There is evidence that the more metal-rich stars in ω Centauri are younger. NGC 2808 has three main sequences, with three different inferred He abundances, and the cluster shows a strong extension of the stellar distribution in [Na/O]. Double subgiant branches are seen in the clusters NGC 1851, NGC 6388 and M54, and the subgiant splitting in NGC 1851 appears to be associated with chemical abundance differences.

Although most of the multiple-population clusters are relatively massive, not all of the massive clusters show multiple populations: 47 Tuc is an example of a massive cluster with a single population.

The multiple main sequences are believed to require different He abundances, with values as high as Y ~ 0.4 to generate the main sequence splitting and the associated horizontal branch morphology. The observed abundances in NGC 2808 provide a constraint on the enrichment scenario: it must avoid enriching the stars in CNO and heavier elements like Fe and the α-elements. Current ideas include pollution by high temperature H-burning in a first generation of massive asymptotic giant branch

(AGB) stars or rapidly rotating massive stars. At least two generations of star formation are needed in such clusters, and the main sequence splitting requires the process to generate discrete levels of Y, not just a spread in Y.

Other ideas include the enhanced He coming from first star enrichment, and the possibility that at least some GCs are the nuclei of primodial dwarf galaxies in which the He had gravitionally settled in their dark matter mini-halos.

At this stage, the enrichment scenario that led to the main sequence splitting in ω Centauri and NGC 2808 is far from understood.

Some of the intermediate-age globular clusters in the LMC also show multiple subgiant branches. NGC 1846 is an example. This cluster has an age of about 2 Gyr: if its subgiant splitting is due to an age difference between the branches, the corresponding age difference is about 300 Myr. Such an age difference could be associated with the merger of binary clusters or with multiple star formation episodes. The much younger LMC cluster, NGC 1850, with an age of about 90 Myr, provides encouragement for both scenarios: it is a binary system and is surrounded by an envelope of gas which would provide fuel for a later episode of star formation.

Light element anomalies

Most globular clusters appear to be homogeneous in their internal stellar [Fe/H] and α-element distributions, but this is not the case for the lighter elements. All GCs with adequate stellar abundance data show a marked anticorrelation of stellar [Na/Fe] with [O/Fe] within individual clusters, with spreads in [Na/Fe] and [O/Fe] exceeding 1 dex in some systems. This anticorrelation is not seen among the field stars with similar [Fe/H] abundances, so the Na-O anomaly is clearly related to the cluster environment, but how is not yet understood. The extent of the [Na/O] spread is related to the maximum effective temperature of the horizontal branch stars in the cluster. Other light-element abundance relations within clusters include the Na-Li and Mg-Al relations and the long-known CNO anomalies. These relations are seen down to the main sequence in some clusters, so they are believed to be imprinted on the cluster stars at birth.

Again, the primary idea is that pollution by high temperature H-burning in a first generation of massive AGB stars or rapidly rotating massive stars is responsible. At least two generations of star formation in GCs are again needed. The details are still far from understood.

The observation that the Na-O anticorrelation is not seen in the halo field stars may place a limit on the contribution of dissolving GCs to the Galactic stellar halo. However it is possible that those GCs that are not going to survive are mostly destroyed quite quickly, on timescales ~ 50 Myr. If the source of the Na-O anticorrelation takes longer to act (e.g., if AGB stars are involved), then the dissolving clusters would not have suffered the light element evolution and so would not affect the Na-O properties of the Galactic halo.

The idea that large and inhomogeneous clusters like ω Centauri are the surviving nuclei of accreted and stripped galaxies has been around for about 20 years and may be relevant to these problems of chemical inhomogeneity. The nuclei of low luminosity spiral galaxies are much like massive GCs in velocity dispersion, mass, surface density and sub-solar metallicity, and some show direct spectroscopic evidence for continuing episodic star formation. For the nuclei of star-forming galaxies, star formation in the surrounding galaxy can provide multiple generations of chemical enrichment. The problem is to get the enriched gas into the nucleus: this is likely to be a sporadic dynamically driven process, delivering discrete levels of enrichment at a few particular times.

Globular cluster systems

The relation between the chemical properties of globular cluster systems and the underlying stellar population of the parent galaxy remains poorly understood. New results on the cluster system of NGC 5128 show that most of its GCs are old and their metallicity distribution function peaks at a similar abundance to the field stars. The clusters show a fairly wide range of [α/Fe], but the [α/Fe] values appear uncorrelated with metallicity or cluster age.

The GC system of M31 includes clusters that are more extended than Galactic GCs of similar absolute magnitude. These clusters appear to be of intermediate luminosity ($-8 < M_v < -5$) and it is these extended clusters that fall in the gap between the Galactic GCs and dSph galaxies in the (M_v, r_h) plane.

Some of the old GCs in elliptical galaxies appear to be extremely α-enhanced – by more than 0.5 dex. The corresponding yields require very rapid enrichment on Myr timescales only by very massive stars (> 20 $M_\odot$).

Dwarf spheroidal galaxies

The dark matter content

A large amount of new kinematical data has been acquired for several of the most recently discovered low luminosity dSph galaxies. Like most dSph galaxies, these faint systems are dominated dynamically by their dark matter, with M/L ratios between about 100 and 1000. The kinematical data allow the mass of dark matter within the region populated by stars to be estimated. It turns out that the dark matter mass within a standard radius of 300 pc is almost the same for all known dwarf spheroidals, at about 10^7 $M_\odot$, although these galaxies have stellar masses from about $10^{2.5}$–10^7 $M_\odot$. The corresponding virial dark mass for these systems is probably much larger, ~ 10^9 $M_\odot$.

Dynamical analysis of the velocity dispersion profiles and the stellar surface density distributions indicates that the dark halos of dSph galaxies have cores (rather than cusps), with central densities 0.1 $M_\odot$ pc^{-3}.

The stellar mass-metallicity relation for the dSph galaxies described above indicates that the present baryon content was established very early in the luminous life of these systems. Why do the baryon masses vary so widely (by ~ 10^5), although their dark matter masses within 300 pc are so similar? Were the baryons in the faintest systems lost during their early evolution, or were they never acquired? It may be that, at such low dark halo masses, the acquisition of baryons is a stochastic process.

Star formation history and chemical evolution

The dSph galaxies show a great range of star formation histories. All appear to have old populations. Several show very clear multiple episodes of star formation in their stellar colour-magnitude distributions. As mentioned above, there is a marked environmental effect in the distribution of systems with different star formation histories: the incidence of more recent star formation increases with Galactocentric radius. The relevant enviromental factor is not yet clear: is it tidal interaction, ram pressure stripping, or photoevaporation? In those dSph galaxies with extended star formation histories, where does the gas come from to fuel the extended star formation?

New colour-magnitude diagrams for large numbers of stars in several of the dSph galaxies (Draco, Ursa Minor, Sextans) delineate their different evolved star populations and show similar rich blue straggler sequences. Blue stragglers are often interpreted in terms of binary star mergers: the implications of these new data are not yet clear.

Detailed abundance data for many elements are now available for large samples of stars in several dSph galaxies. Each galaxy shows a wide spread in [Fe/H], and some show abundance gradients. The relationship between [Fe/H] and the abundances of other elements differs from galaxy to galaxy. The most metal-poor stars are mostly α-enriched, but the [α/Fe] ratio begins to decrease with increasing [Fe/H] at different [Fe/H] abundances from galaxy to galaxy, reflecting the different star formation timescales. This is unlike the rather well-defined [α/Fe]-[Fe/H] relation for the stars in the Solar Neighbourhood. Similar diversities are seen in s-process element abundances within the dSph galaxies, generated by AGB star evolution and reflecting differences in the gradual rise of s-process abundances with time.

Stars in the low luminosity Hercules dSph show near-solar [Ca/Fe], but an unusually high [Mg/Ca] ratio, in excess of +1, suggesting chemical enrichment by just one or two high mass SNe II with progenitor masses ~ 35 $M_\odot$.

Recent abundance studies of the ultra-faint dSph galaxies show that their metallicity distributions extend down below [Fe/H] = −3. The metal-poor end of the stellar metallicity distribution function (MDF) for the dSph systems now looks more like that for the Galactic halo. The dSph galaxies appear to follow a stellar luminosity-metallicity relation extending down below [Fe/H] = −3, although their dark matter masses within 300 pc radius are all very similar. This indicates that their diverse chemical properties are evolutionary rather than acquired.

The distribution of stellar abundances along the Sgr stream shows a strong gradient away from the core of the Sgr system. The overall abundance signatures (α, s-process elements) look more like those in the Large Magellanic Cloud (LMC) than in other dSph galaxies.

Other related issues

- New stellar abundance data in the Galactic Bulge show that the mean abundance decreases with increasing Galactic latitude. This finding may argue against the formation of the Bulge by secular processes.
- The ACS survey of Galactic globular clusters provides a new age-metallicity relation for the clusters. Clusters with [M/H] < −1.3 are all old. Clusters with [M/H] > −1.3 split into two families. One family is all old, as old as the metal-poor clusters. The other family, which includes several clusters associated with recent likely accretion events, shows a clear age-metallicity relation with age decreasing as [M/H] increases.
- The metal-poor halo of M31 extends out to a radius of at least 165 kpc, with a mean abundance of ~ −1.4 at a radius of 100 kpc.
- New methods have been developed to measure accurate element abundances of extragalactic globular clusters from high resolution spectra of their integrated light.
- New data on stellar ages and metallicities in the disc of the LMC, at radii in the range 3–8 degrees from the LMC centre, show that the age-metallicity relation is very similar in each of the fields.

Right. A colour image of the Galactic globular cluster NGC 6397. The image is a composite of exposures in the *B*-, *V*- and *I*-bands obtained with the Wide Field Imager (WFI) at the 2.2-m MPG/ESO telescope.

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Back Cover Picture: A colour composite image of the Galactic globular cluster ω Centauri, which displays abundance anomalies and multiple main sequences, and emerged as a reference object of its class from the conference reviews. The image was formed from Max-Planck/ESO 2.2-m telescope Wide Field Imager *B*-, *V*- and *I*-band exposures. See ESO Release 44/08 for more details.

Front Cover: Based on the conference announcement poster designed by ESO/L. Calçada.