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?

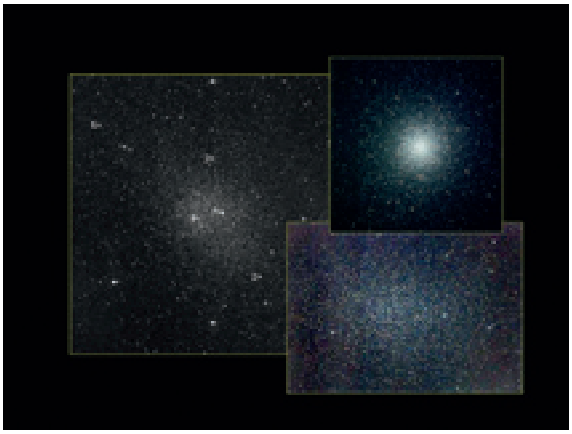

Figure 1. An image showing a globular cluster (upper right), a dSph galaxy (lower right) and a galaxy, Fornax, that contains a (small) population of globular clusters (the numbered objects in the image to the left). Even here, the considerably higher surface brightness of the globular clusters, compared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

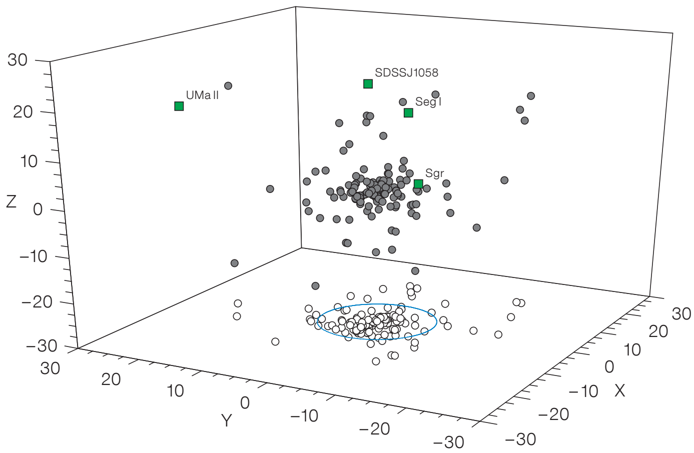

Figure 2. The distribution of inner halo objects as a function of Galactic X, Y and Z coordinates. Grey points are globular clusters, while the green points represent the closest of the recently discovered dwarfs, as well as the Sgr dwarf. Note that nearly all the objects in the inner halo are globulars; 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.

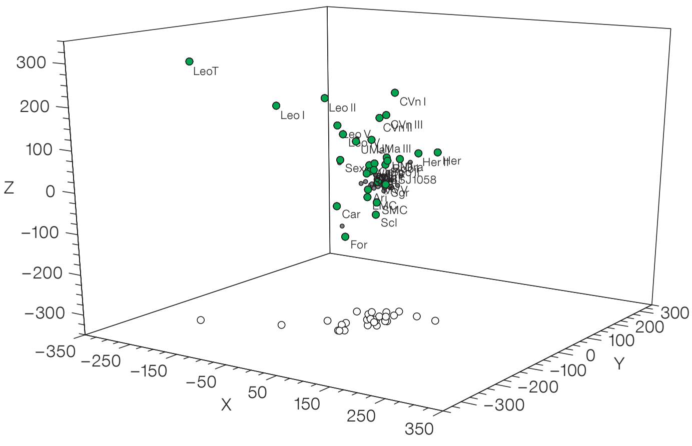

Figure 3. The distibution of objects in the outer Galactic halo. Individual dwarfs are shown as green dots and are labelled by name. The projected positions in the x-y plane are shown at the bottom of the plot as open circles. The asymmetric distribution apparent here is largely due to the uneven sampling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

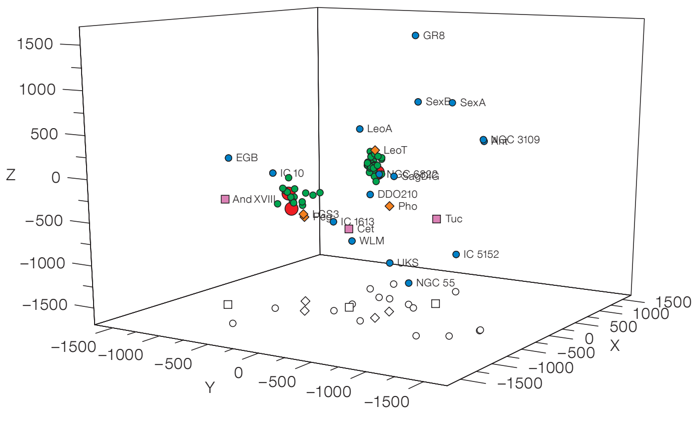

Figure 4. The distribution of all galaxies in the Local Group. Green dots are the dSph galaxies; blue dots the dIrr galaxies. Orange diamonds represent the so-called transition galaxies (see Mateo, 1998), while three remote dSph galaxies are shown as pink squares (Cetus, Tucana and And XVIII). The large 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.

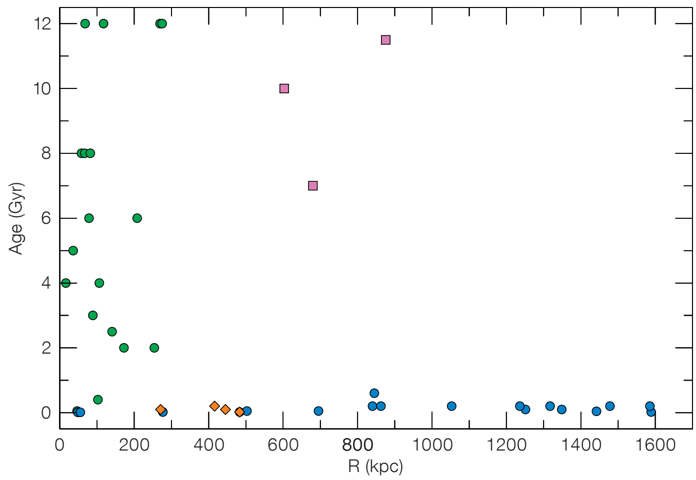

Figure 5. A plot of the ages of the youngest populations as a function of Galactocentric (or, where appropriate, M31-centric) distance (RGC) for Local Group dwarfs. The symbols are the same as in Figure 4. Note the clear progression from dSph, to transition, to dIrr galaxies with increasing RGC. Star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

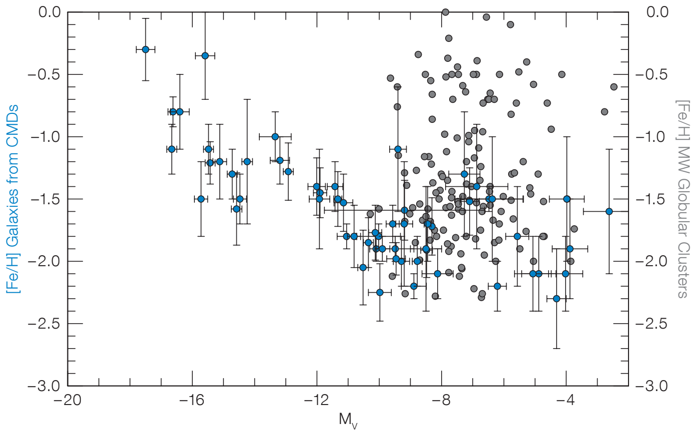

Figure 6. The age-metallicity relation for dwarf galaxies of the Local Group (blue dots) and Galactic globular clusters (grey dots). The mean metallicities of the galaxies are from CMD analyses, with no cuts on the quality of the measurements. Do the dwarfs transition into the clusters in this diagram?

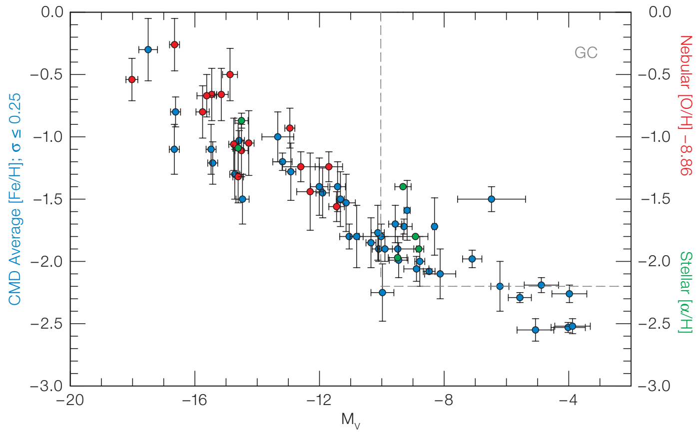

Figure 7. The age-metallicity relation for dwarf galaxies of the Local Group from high quality CMD and spectral analyses ($\sigma_{[O/Fe]} \leq 0.25$ mag; blue dots), nebular abundances (on a scale set by the solar [O/Fe] value; red dots), and from stellar α-abundances (green dots). The realm of globular 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 addi-

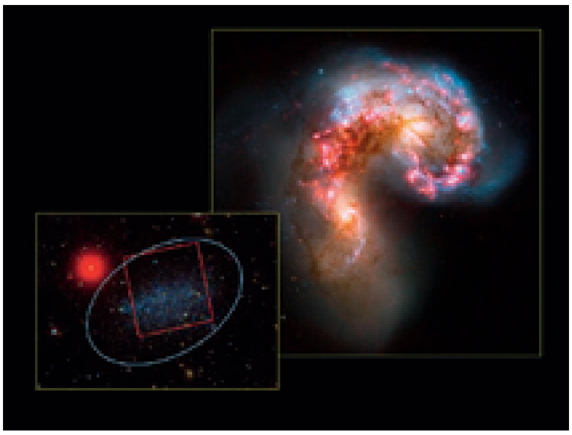

Figure 8. Dwarf galaxies seem to have followed comparatively sedate star formation histories, devoid of much contamination by supernovae (left). Globular clusters seem to have formed in far more violent conditions (right). Together, they may allow us to piece together many of the key elements of galaxy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

tion 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-enrichment 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 SN II 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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