Chemical Evolution of Dwarf Galaxies and Stellar Clusters: Conference Summary

Kenneth C. Freeman
Research School of Astronomy and Astrophysics, The Australian National University, Canberra, Australia

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.