The General Assembly of Galaxy Halos: Structure, Origin and Evolution
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Globular clusters in M31, Local Group, and external galaxies

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Abstract. Throughout most of the Local Group, globular clusters (GCs) remain recognisable as extended objects in ground-based images taken in good seeing conditions. However, studying the full extent of the GC systems is challenging because of the large sky area that needs to be surveyed and recent years have seen dramatic progress in our knowledge of GC populations in nearby galaxies, thanks to large imaging surveys. At the same time, techniques for deriving detailed abundances from integrated-light spectra of GCs are maturing so that detailed comparisons of the chemical composition for GCs in different galaxies can now be made. Such comparisons may shed important light on the properties of proto-galactic fragments that were accreted onto galaxy halos. Nevertheless, our census of Local Group GCs probably remains far from complete, in particular at low luminosities and for very extended clusters.

Keywords. Globular Clusters; Galaxies

1. Introduction

Globular clusters (GCs) are classical tracers of galaxy halos. Although it now possible to image diffuse stellar halo light to impressively low levels of surface brightness (e.g., Mihos and McConnachie, these proceedings), GCs can be identified and properties such as ages, chemical composition, and kinematics can be studied in detail at much greater distances than for individual stars. In the context of galaxy halos, it is of particular relevance to note that, although metal-poor halos typically account for only a small percentage of the total stellar mass in a galaxy, the fractions of the total GC populations that are associated with halos can be large. This means that GCs can be efficiently employed to study these, otherwise difficult to access, components of galaxies.

While some of the brighter stellar clusters in the Magellanic Clouds were already catalogued by Dunlop (1828) and included in Herschel's *Catalogue of Nebulae and Clusters of Stars* (Herschel 1864), the study of extragalactic globular clusters started in earnest with Hubble's identification of 140 GC candidates in M31 (Hubble 1932). Hubble found a mean magnitude of $\langle V \rangle = 16.7$ for the M31 GCs, corresponding to $\langle M_V \rangle \approx -7.85$ when using the modern values of the distance and extinction towards M31 (Riess *et al.* 2012; Schlafly & Finkbeiner 2011). This is already quite close to modern estimates of the turn-over of the globular cluster luminosity function (GCLF) in M31 (Huxor *et al.* 2014) and other galaxies (e.g. Larsen *et al.* 2001). More detailed photometric work (Kron & Mayall 1960) showed the integrated colours of M31 GCs to be somewhat redder than those of their Milky Way counterparts, although uncertain corrections for interstellar reddening made it difficult to conclude whether this difference was intrinsic to the clusters (e.g., due to differences in age and/or metallicity) or could be caused by different amounts of extinction. From spectroscopic and photometric observations, van den Bergh (1969) found that GCs in M31 are indeed more metal-rich on average than those in the Milky Way, a result that has since been confirmed by many other studies (Huchra *et al.* 1991; Barmby *et al.* 2000; Perrett *et al.* 2002; Beasley *et al.* 2005; Caldwell *et al.* 2011). In the same paper, van den Bergh (1969) also noted that the GCs in the Fornax dwarf spheroidal galaxy appeared to have very low metallicities compared to those in the Milky Way and M31. It was thus clear already from these early studies that the properties of GC systems in different galaxies can differ substantially, and that such differences may provide important hints to the formation and chemical enrichment histories of their parent galaxies.

2. GCs in the Local Group: overview

Table 1 lists the Local Group member galaxies with known GC populations, based primarily on the catalogue by Harris *et al.* (2013). It is worth noting that this catalogue contains data for more than 400 extragalactic GC systems, the most distant of which are located well beyond the Coma galaxy cluster. Clearly, within the Local Group the GC system of M31 is the most populous by a large margin in terms of absolute numbers. However, when normalising the numbers of GCs to the host galaxy luminosities, expressed by the GC specific frequency ($S_N \equiv N_{\rm GC} \times 10^{0.4(M_V+15)}$; Harris & van den Bergh 1981), the well-known trend for S_N to increase for lower luminosity galaxies becomes apparent. Data for larger samples of galaxies show that the behaviour of S_N versus host galaxy absolute magnitude is actually U-shaped with a minimum between $M_V \sim -18$ and $M_V \sim -20$ (Harris *et al.* 1991; Miller & Lotz 2007; Peng *et al.* 2008; Georgiev *et al.* 2010; Harris *et al.* 2013; Mieske *et al.* 2014).

Although the galaxies in Table 1 are generally well studied, the numbers of known GCs have increased significantly in recent years for many of them. The PAndAS survey has revealed about 100 previously uncatalogued GCs in the outer parts of M31 (Huxor *et al.* 2008; 2014). Another interesting case is NGC 6822 ("Barnard's galaxy") which, until a few years ago, was thought to host only a single old GC, whereas 7 additional clusters have recently been identified in this galaxy (Hwang *et al.* 2011; Huxor *et al.* 2012). Recent additions to the census of Local Group GCs also include three clusters in NGC 147 and one in NGC 185 (Veljanoski *et al.* 2013).

For completeness, Table 1 also includes Local Group members (according to Mateo 1998) brighter than $M_V = -13$ (i.e., corresponding to the Fornax dSph) that do *not* host known GC populations. It should be clear from the preceding remarks that absence of evidence is, especially in these cases, not necessarily evidence of absence, particularly since some of these systems are quite distant and might merit further study. In the case of M32, however, the absence of a significant GC population does appear to be real, and may be attributable to dynamical erosion processes and/or stripping (Brockamp *et al.* 2014).

3. GC systems and the accretion histories of galaxy halos

3.1. *Metallicity distributions*

As already noted, the GC system of M31 is by far the richest in the Local Group. Based on spectroscopy of 150 GCs in M31, Huchra *et al.* (1991) found the metallicity distribution to be broad, ranging between [Fe/H] ≈ -2 and [Fe/H] ≈ 0, i.e., a range comparable to that seen in the Milky Way, with no obvious trend with luminosity (i.e., no evidence for significant mass-dependent self-enrichment within GCs) and only a weak radial gradient.

A recurrent theme in the discussion of the M31 GC metallicity distribution is the question of *bimodality*. In the Milky Way there is a fairly clear separation into a metal-poor group ($\langle$[Fe/H]$\rangle \approx -1.5$) with halo-like kinematics and spatial distribution, and a

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Table 1. Globular cluster systems in the Local Group.

Galaxy	M_V	N_{GC}	S_N
M31	−21.8	∼ 450	0.86
Milky Way	−21.3	∼ 160	0.48
M33	−19.0	∼ 50	∼ 1.3
LMC	−18.4	16	0.70
SMC	−16.8	1	0.19
NGC 205	−16.7	11	2.3
NGC 6822	−15.5	8	5.0
NGC 147	−15.5	10	6.3
NGC 185	−15.4	8	5.5
WLM	−14.8	1	1.2
Sagittarius	−13.9	8	22
Fornax	−13.0	5	32
Galaxies with no known GCs:			
M32	−16.7		
NGC 3109	−15.7		
IC 10	−15.7		
IC 1613	−14.7		
Sext A	−14.6		
Sext B	−14.2		

more metal-rich population ($\langle[\mathrm{Fe/H}]\rangle \approx -0.5$) that is more naturally associated with the bulge and/or thick disc (Zinn 1985; Minniti 1996). This distinction is much less clear in M31; the metallicity distribution found by Huchra *et al.* (1991) does not display clearly distinct peaks, although a stronger hint of bimodality is present in the larger sample (229 GCs) of Perrett *et al.* (2002). Barmby *et al.* (2000) found evidence for two peaks at $[\mathrm{Fe/H}] = -1.4$ and $[\mathrm{Fe/H}] = -0.6$, i.e., quite similar to the peaks in the MW metallicity distribution. More recently, however, Caldwell *et al.* (2011) analysed the metallicity distribution of 322 GCs with spectroscopic observations and found no evidence of bimodality.

Bimodal *colour* distributions are commonly observed in extragalactic globular cluster systems (Elson & Santiago 1996; Kundu & Whitmore 2001; Larsen *et al.* 2001; Peng *et al.* 2006), the usual interpretation being that they reflect underlying bimodal *metallicity* distributions. However, non-linearities in the colour-metallicity relations may cause significant distortion of metallicity distributions when mapped to colour space. In particular, it has been argued that the rapid change in horizontal branch morphology of old stellar populations at intermediate metallicities can cause an inflection point in the colour-metallicity relation, so that clusters will tend to avoid intermediate colours. This effect can potentially produce bimodal colour distributions even if the underlying metallicity distributions are unimodal (Yoon *et al.* 2006; Cantiello & Blakeslee 2007). While the GC metallicity distributions for M31 discussed above are generally based on spectroscopic measurements, the relations between spectroscopic line indices and metallicities may be subject to similar effects (Kim *et al.* 2013) and indeed Caldwell *et al.* (2011) argued that non-linear transformations were required in their analysis.

Despite these complications, it is clear that the metallicity distributions of GC systems can differ substantially (e.g., Larsen *et al.* 2005), and at least in the Milky Way (where metallicities can be measured directly via high-dispersion spectroscopy of individual stars), the evidence for bimodality is strong. Presumably, these differences reflect differences in the corresponding formation- and assembly histories of the GC systems. Historically, bimodal GC metallicity distributions were predicted as a consequence of the "major merger" formation scenario for elliptical galaxies, in which the metal-poor GCs would represent the original (halo) GCs in gas-rich disc galaxies, and the metal-rich clusters were formed in the starburst accompanying the merger (Schweizer 1987; Ashman

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& Zepf 1992). Other scenarios included accretion of metal-poor GCs from dwarf galaxies (Côté *et al.* 1998) or an *in-situ* "multi-phase" collapse (Forbes *et al.* 1997). Modern theoretical work now seeks to reproduce GC metallicity distributions in the context of hierarchical galaxy formation models and incorporates elements of all of the older ideas (Muratov & Gnedin 2010; Tonini 2013; Kruijssen 2015). By coupling cosmological merger trees with plausible assumptions about chemical evolution, GC formation efficiencies, and cluster disruption, such models are starting to provide more detailed insight into some of the mechanisms that may shape GC metallicity distributions. For example, galaxies that have accreted a larger fraction of their mass from small satellites may be expected to have a more prominent metal-poor GC population (Tonini 2013). As both models and observations continue to improve, other properties of GC sub-populations such as kinematics, detailed abundances, and age distributions, may provide important constraints on the accretion- and merger histories of galaxies.

3.2. *GCs in halos vs. dwarf galaxies*

Because of the long dynamical time scales in the outer parts of galaxy halos, this is where the signatures of accretion events are expected to be most readily visible. However, the low surface brightness and large extent on the sky (particularly for Local Group galaxies) represent significant observational challenges. Within the Local Group, the full extent of the M31 GC system has only recently become clear, thanks in large part to the PAndAS survey which has now mapped the M31 GC population to distances beyond 100 kpc from the centre of the galaxy (Huxor *et al.* 2008; 2014). Additional GC candidates beyond 100 kpc have also been identified in SDSS imaging (di Tullio Zinn & Zinn 2013). It is now clear that the M31 GC system is significantly more extended than that of the Milky Way; currently 91 GCs are known with (projected) galactocentric distances of $R_{\rm proj} > 25$ kpc and 12 with $R_{\rm proj} > 100$ kpc in M31. In the Milky Way the corresponding numbers are ~ 13 and ~ 1, respectively (Huxor *et al.* 2014), so the difference remains quite significant even after accounting for the overall greater number of GCs in M31. The spatial distribution of the GCs in M31 appears to correlate well with the stellar overdensities observed in the halo, from which it has been suggested that up to $\sim 80\%$ of the outer halo GCs in M31 may have been accreted (Mackey *et al.* 2010). Interestingly, searches for GCs at large distances from the centre of the third spiral in the Local Group, M33, have revealed only a handful of objects with $R_{\rm proj} > 10$ kpc (Cockcroft *et al.* 2010).

3.2.1. *Luminosity functions*

It was noted by van den Bergh (1998) that the GCs in the outer part of the Galactic halo (beyond $R = 80$ kpc) have a luminosity function which differs significantly from the LF seen in the inner part of the GC system, which is peaked at $M_V \approx -7.5$. The outer halo GCs are mostly fainter than $M_V = -6$, but one cluster (NGC 2419) is brighter than $M_V = -9$. Van den Bergh (1998) thus suggested that the GCLF in the outer Galactic halo may be bimodal, and noted that the Sagittarius dwarf galaxy appears to display a similarly bimodal GCLF, suggesting that the Searle-Zinn fragments that formed the halo may have resembled the Sagittarius dwarf. It has further been suggested that an accretion origin is especially likely for the "young halo" clusters in the Milky Way (Mackey & van den Bergh 2005; Forbes & Bridges 2010).

Drawing definitive conclusions from the small number of clusters in the outer Milky Way halo is difficult, but better statistics are available in M31. Huxor *et al.* (2014) found a similarly bimodal GCLF in the outer halo of M31, with peaks at $M_V \sim -7.5$ and at $M_V \sim -5.5$, although the exact location of the fainter peak is uncertain because of completeness effects. Again, this resembles the GCLF of the Sagittarius dwarf, and would

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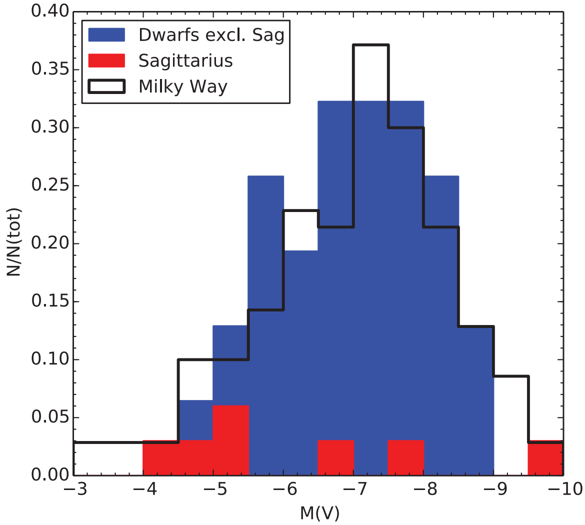

Figure 1. Luminosity functions for GCs in the Milky Way, Local Group dwarf galaxies (excl. Sagittarius) and the Sagittarius dwarf.

appear to be consistent with the idea that many of the outer halo GCs in M31 have been accreted from Sagittarius-like fragments.

Given that the Sagittarius dwarf is currently in the process of being accreted by the Milky Way, along with its ~ 8 GCs, it is perhaps not surprising that it has been used as a benchmark for comparison with halo GCs. Nevertheless, it may be worth asking how representative the GC system of the Sagittarius dwarf is of GCs in dwarf galaxies in general. Figure 1 shows the GC luminosity functions for the Milky Way, the Sagittarius dwarf, and other dwarf galaxies (with $-16 < M_V < -13$) in the Local Group. It is clear that the GCLF in Sagittarius is indeed quite different from the global GCLF in the Milky Way; however, it also differs from the combined GCLF of the remaining dwarfs. Indeed, the GCLFs of the remaining dwarfs (individually or combined) are consistent with being drawn from that of the Milky Way, with a K-S test yielding a p-value of 0.69 when comparing the Milky Way and combined dwarf galaxy GCLFs. Instead, the comparison of the Sagittarius vs. Milky Way GCLFs yields $p = 0.03$. It would be interesting to investigate in more detail to what extent these differences can be attributed to effects of dynamical evolution and the special circumstances of Sagittarius, in particular.

3.2.2. *Metallicities*

A comparison of the chemical composition of GCs in the halos of large galaxies with those in dwarf galaxies may provide additional clues to the properties of the fragments that built up halos. In this section we comment on the overall metallicities; the detailed chemical composition will be considered in Sect. 3.2.3.

As noted in the introduction, the GCs in the Fornax dSph are much more metal-poor on average than those in the Milky Way halo. More generally, there is a correlation between the metallicities of GC (sub)-populations and host galaxy luminosity/mass (e.g. Larsen *et al.* 2001; Peng *et al.* 2006). One difficulty associated with measuring accurate metallicities at the extremes of the distribution is that traditional integrated-light methods (broad-band colours, spectroscopic line indices) rely on calibrations that are less well established at low metallicities. However, most studies agree that the four most metal-poor clusters in Fornax (Fornax 1, 2, 3, and 5) have metallicities of [Fe/H] ≈ -2 or

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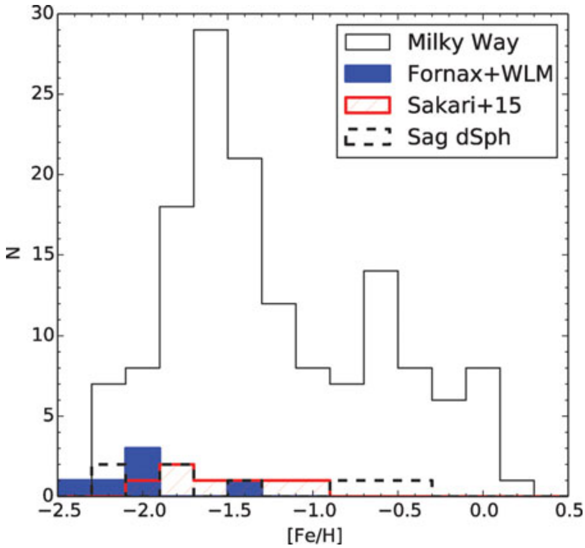

Figure 2. GC metallicity distributions for the Milky Way, Fornax dSph, Sagittarius dwarf, and outer halo GCs in M31.

below (Strader *et al.* 2003), which is significantly lower than the typical metallicities of halo GCs in the Milky Way or M31. Abundance measurements that do not rely on intermediate calibration steps are now available from high-dispersion spectroscopy, either for individual stars (Fornax 1, 2, and 3; Letarte *et al.* 2006) or from integrated light (Fornax 3, 4, and 5; Larsen *et al.* 2012). These measurements confirm that Fornax 1, 2, 3, and 5 all have $[Fe/H] < -2$, whereas Fornax 4 has $[Fe/H] \approx -1.4$.

Figure 2 shows the metallicity distributions for GCs in the Milky Way and Sagittarius (Harris 1996), the Fornax and WLM dwarf galaxies (Larsen *et al.* 2012; 2014), and outer M31 halo GCs from PAndAS (Sakari *et al.* 2015). The M31 outer halo GCs have similar metallicities to halo GCs in the Milky Way, whereas the Fornax and WLM GCs are evidently much more metal-poor. A K-S test yields a probability of only 0.003 that the Fornax+WLM GCs are drawn from the same metallicity distribution as the Milky Way GCs (restricting the comparison to $[Fe/H] < -1$). For Sagittarius, the corresponding comparison yields $p = 0.15$, i.e., no significant difference.

From these comparisons, it appears that the LFs and metallicity distributions of GCs in the *outer halos* of M31 and the Milky Way are similar to those of the Sagittarius dwarf galaxy and that the GCs in the outskirts of these large spirals might indeed have originated in fragments resembling Sagittarius. For the halo GC populations as a whole, the situation is less clear. While the metallicity distributions remain consistent with those in Sagittarius, the GCLFs are quite different. Clearly, a direct comparison of GCLFs is complicated by the possible role of dynamical evolution, which may have affected the GCLFs in different environments differently. It appears unlikely, however, that a significant fraction of the GC population in the large spirals originated in fragments resembling the Fornax dSph, as the metallicities of the Fornax GCs are too low.

3.2.3. *Detailed chemical composition*

While GCs lend themselves to spectroscopic studies at relatively high spectral resolution because of their modest velocity dispersions (typically 5–10 km s^{-1}), most spectroscopic work on GCs has, until recently, been based on methods developed primarily for analysis of galaxies at relatively low spectral resolution. However, in recent years several groups have developed analysis techniques that can take advantage of the large amount of information that is potentially available in an integrated-light, high-dispersion GC spectrum (McWilliam & Bernstein 2008; Larsen *et al.* 2012; Sakari *et al.* 2013; Colucci *et al.* 2014). While the approaches adopted by the various authors differ in detail, they may in general be seen as extensions of classical simple stellar population models to high spectral resolution, in which abundances of individual elements can be varied and the effect on the integrated spectra compared with observations.

It now appears within reach to apply "chemical tagging" (Freeman & Bland-Hawthorn 2002) to identify groups of GCs that may have a common origin. For example, one may exploit the differences in elemental abundance ratios as a function of metallicity in dwarf galaxies when compared with larger galaxies, such as the shift in the location of the "knee" in the [α/Fe] vs. [Fe/H] relation as a function of host galaxy mass (Tolstoy *et al.* 2009). This shift is well established for field stars, and is also seen in the GC system of the Fornax dSph, where Fornax 4, the most metal-rich of the clusters, has a noticeably lower [α/Fe] ratio than GCs of comparable metallicity in the Milky Way, but following the trend seen for field stars in Fornax (Larsen *et al.* 2012; Hendricks *et al.* 2014). Combining abundance information with other diagnostics, such as kinematics and spatial location, may provide a promising avenue towards identifying groups of GCs that once belonged to a common progenitor. Using this approach, Sakari *et al.* (2015) have identified several GCs that might be associated with stellar streams in the outer M31 halo.

A second potential application is to study the phenomenon of multiple stellar populations in GCs using integrated-light observations. In Milky Way GCs, it is now well established that the abundances of light elements (e.g., C, N, O, Na, Mg, Al) display substantial star-to-star variations within a given cluster (e.g., Carretta, Piotto, these proceedings). Integrated-light observations of extragalactic GCs have, in several cases, revealed depleted [Mg/Fe] ratios in clusters that otherwise appear to have normal [α/Fe] ratios, as well as enhanced [Na/Fe] ratios (Colucci *et al.* 2009; Larsen *et al.* 2012,2014; Sakari *et al.* 2015). These observations may be indicative of the Mg/Al and Na/O anticorrelations, whereby a fraction of the stars would have depleted Mg and enhanced Na abundances, thus driving the mean abundances of these elements down and up, respectively. A particularly exciting prospect is that such methods might be used to search for abundance anomalies in young massive clusters, such as those in the "Antennae" galaxies, which are generally too distant for individual stars within the clusters to be studied in detail spectroscopically.

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