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# Globular Clusters and Dwarf Galaxies

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**Abstract.** This contribution concentrates on a comparison between the globular cluster systems of Local Group dwarf galaxies and the clusters of the outer halo of the Galaxy. It reveals that in terms of structural parameters, luminosities, ages, and abundances, the combined dwarf and outer halo cluster systems are quite similar. This similarity supports the hypothesis that a significant fraction of the outer Galactic halo may have originated in the disruption of dwarf-galaxy-like systems.

## 1. Introduction

In 1938 Shapley announced the discovery of "A Stellar System of a New Type" in the constellation of Sculptor. This system was novel in that it had the smooth density profile of a low central concentration globular cluster, yet if its brightest stars were of the same absolute magnitude as those in globular clusters, it had to be much larger and much more distant than any Galactic globular cluster known at that time. Shapely (1938) argued that the most appropriate interpretation of the Sculptor system was as "a super-cluster of the globular type", a view supported by the discovery soon afterwards of "cluster-type" (i.e. RR Lyrae) variables in this system (Baade & Hubble 1939). We now know this system as the Sculptor dwarf spheroidal (dSph) galaxy, a relatively nearby example of a common type of low luminosity dwarf galaxy. The view of dSph galaxies as "puffed-up globular clusters" remained prevalent for a long time, but we now recognise that as far too simple an interpretation: dSph galaxies are independent galaxies that have undergone their own distinct individual evolution. In particular, they characteristically show significant internal abundance ranges, frequently have had extended star formation histories, and are repositories for large amounts of dark matter. Conversely, globular clusters most probably form as part of some larger scale star formation process and, in general, do not show internal abundance ranges, at least for elements like Fe, Ca, etc. They are also each individually effectively a single age population, and apparently do not contain any dark matter. They are therefore very different objects from dSph galaxies, even if their total luminosities are sometimes comparable.

In this review I will first address the question of the occurrence of globular clusters in dwarf galaxies. Then, given the increasing evidence that the disruption of dwarf galaxies may have contributed significantly to the build-up of the Galactic halo, I will compare the properties of the globular cluster systems of nearby dwarf galaxies with those for globular clusters in the outer Galactic halo.

## 2. Globular Clusters in Dwarf Galaxies

The first question to address as regards globular clusters in dwarf galaxies is "How frequently do globular clusters occur?". For dwarf irregular (dIrr) galaxies there is not a lot of detailed information. Hodge et al. (1999) have used HST/WFPC2 imaging to show that the luminous ($M_V \approx -8.8$) star cluster associated with the Local Group dIrr WLM is apparently a geniune old metal-poor globular cluster, but most other Local Group dIrr galaxies don't contain any objects that are clearly old centrally concentrated star clusters. The exception is the SMC which does contain a number of centrally concentrated star clusters, which have a variety of ages (e.g. Da Costa 2002). However, only NGC 121 has an age comparable to the age of the Galactic halo globular clusters. Similarly, NGC 6822 possess a small number of centrally concentrated star clusters which also have a variety of ages, and one, Hubble VII, appears to be an old metal-poor globular cluster (Cohen & Blakeslee 1998; Chandar et al. 2000).

On the other hand, most dwarf elliptical (dE) galaxies of sufficient luminosity do contain star clusters whose colors suggest they are old and metal-poor (e.g. Miller et al. 1998 and references therein). Miller et al. (1998) show that nucleated dEs tend to have a higher specific frequency ($S_N$) of globular clusters than non-nucleated systems, but both types show an indication that $S_N$ increases with decreasing luminosity. Of course such a trend does not continue indefinitely as low luminosity dEs generally don't possess any globular clusters. This result immediately brings up a second question: "How faint can a dE galaxy be and still have globular clusters?".

The Milky Way dSph companion Fornax, which has $M_V \approx -13.2$ and 5 globular clusters, is usually taken as the faintest dE with a globular cluster system. However, recent results from HST/WFPC2 are offering new insight into this question. In particular, Karachentsev et al. (2000a,b) have identified a number of globular clusters associated with dE galaxies in the M81 group. Their searches have revealed single globular clusters in the dEs Kar 61 ($M_V \approx -13.9$), Kar 63 (–13.2), kk 077 (–12.8), DDO 78 (–12.8) and BK 6N (–11.9) but no candidates were found in Kar 64 (–13.4), FM 1 (–11.5) and kkh 57 (–10.9). These candidate globular clusters have $M_V$ values between $\sim -6$ and –8.5. When combined with the M81 group dE data of Caldwell et al. (1998), namely one globular cluster candidate in F8D1 (–14.3) but none in BK 5N (–11.3), these results suggest that dEs more than a magnitude fainter than Fornax can possess globular clusters, though admittedly, the absolute magnitude of BK 6N is uncertain (Karachentsev et al. 2000a). However, the high specific frequency of Fornax ($S_N \approx 28$) remains unusual – although the cluster searches in the M81 dEs are not claimed to be complete, the $S_N$ values appear to be consistent with typical values for non-nucleated dEs ($S_N \approx 6$ at $M_V \approx -13.5$, Miller et al. 1998), rather than higher values.

## 3. The Globular Cluster Systems of Local Group Dwarfs and the Globular Clusters of the outer Galactic halo

In the remainder of this contribution I will focus on the globular cluster systems (hereafter GCS) of relatively nearby dwarfs, for the simple reason that for these

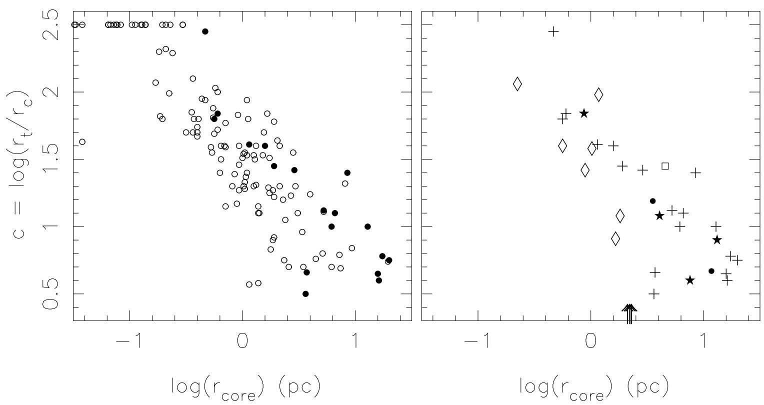


Figure 1. In the *left panel* the filled symbols are globular clusters in the outer Galactic halo ($R_{GC} \geq 20$ kpc) while the open symbols are for the Galactic globulars with $R_{GC} < 20$ kpc. Core-collapse clusters have been plotted with a concentration index $c$ of 2.5. Note the tendency for the outer halo clusters to have larger core radii and lower concentration indices. The *right panel* compares the outer Galactic halo clusters (+ symbols) with the globular clusters in a number of dwarf galaxies. The NGC 205 clusters are shown as open diamonds, the WLM cluster is the open square, the Sgr clusters are the star symbols and the filled circles are the Fornax clusters. According the Rodgers & Roberts (1994), 3 Fornax clusters do not fit King models and thus they do not have $c$ values. The core radii of these clusters are shown by the arrow symbols.

nearer systems it's possible to determine a variety of additional properties beyond integrated magnitudes and colors. This then allows detailed comparisons with the GCS of more luminous galaxies. The comparison system I will use is that of the outer Galactic halo. The reason for this choice is that there is increasing support (e.g. Morrison et al. 2002 and the references therein) for the view that the disruption of dwarf galaxies may have contributed significantly to the build-up of the Galactic halo, particularly as regards its more distant components. We see this process occurring today with the disruption of the Sagittarius dSph. This dSph has (had?) at least four globular clusters associated with it, and once Sgr is completely merged into the halo, i.e. it is recognisable only as the "Sagittarius stream", these globular clusters will become globular clusters in the outer halo of the Galaxy. Indeed, it is conceivable that *all* the outer Galactic halo globular clusters came from the disruption of globular-cluster-containing dwarf galaxies.

## 3.1. Structural Properties and Absolute Magnitudes

As noted by van den Bergh and others (e.g. van den Bergh 2000 and the references therein), the outer halo globular clusters of the Galaxy are somewhat different from the inner halo clusters. In particular, the outer halo clusters tend to be larger and less centrally concentrated (cf. left panel of Fig. 1) and the relative frequency of lower luminosity clusters is notably higher than is the case for the inner halo. These differences are driven to some extent by the fact that the clusters at large galactocentric distances are less affected by the Galaxy's bulge, disk, etc. Consequently, the system of outer halo clusters is "less evolved".

Using data from the Harris (1996; web version June 1999) compilation and excluding the 4 definite Sgr clusters, there are 18 clusters with $R_{GC} \geq 20$ kpc and $\sim$120 clusters with $R_{GC} < 20$ kpc. The division at 20 kpc was chosen because this is the approximate Galactocentric distance of the Sgr clusters. None of the results discussed here are dependent in any substantial way on this choice. Comparing these samples we find, for example, that the fraction of clusters with $r_{core} > 2$ pc is 0.67 for the outer halo, but only 0.18 for the inner clusters. Similarly, the fraction of clusters with concentration index $c \leq 1.5$ is 0.72 in the outer sample, compared to 0.40 in the inner sample. The outer sample also contains no core-collapse clusters whereas $\sim$20% of the inner sample are in this category. As regards total luminosities, in the outer halo 56% are fainter than $M_V \approx -6.2$, while the fraction is only 0.12 for the inner sample. However, the fraction of bright clusters ($M_V \leq -8.0$) is comparable in the two samples: 0.24 for the outer sample as against 0.27 for the inner sample.

For the combined Local Group dwarf galaxy GCS, there are a total of 26 globular clusters (7 in NGC 205 excluding the clusters Hubble V and Lee 9003 as they have ages of $\sim$500 Myr – 1 Gyr, 6 in NGC 185, 3 in NGC 147, 4 in Sgr[1], 5 in Fornax, and 1 in WLM). The NGC 185 and NGC 147 clusters lack surface brightness profile data but such information is available for the remainder, including the NGC 205 clusters (Barmby et al. 2002). The right panel of Fig. 1 shows the (concentration index, core radius) relation for the dwarf galaxy and outer Galactic halo globular clusters. Clearly there is a considerable degree of similarity between the systems. However, it is worth noting that Rodgers & Roberts (1994) showed that of the five Fornax clusters, three apparently do not fit the standard King model profiles. Instead the profiles of clusters 3, 4 and 5 lack the 'tidal truncation' turndown of the model profiles. It will be interesting to see if profiles based on the available HST/WFPC2 data for these clusters confirm the Rodgers & Roberts (1994) results.

In quantitative terms, for the combined dwarf GCS the fraction of clusters with $r_{core} > 2$ pc is 0.53, compared to 0.67 for the outer halo sample, and the fraction of clusters with concentration index $c \leq 1.5$ is 0.69 (excluding the three Fornax clusters) versus 0.72 for the outer halo. The outer halo sample contains no core-collapse clusters and this is also true for the combined dwarf GCS, though Barmby et al. (2002) have suggested that NGC 205 Hubble II may be a candidate core-collapse cluster. In terms of luminosities, the fraction of clusters

[1]This number is probably a lower limit. There are strong suggestions that Pal 12 should also be regarded as a Sgr cluster (Dinescu et al. 2000) and Bellazzini et al. (2002, see also these proceedings) have suggested that NGC 5634, and perhaps other clusters, might also be associated with Sgr. If this is correct, then it has interesting implications for the cluster specific frequency and luminosity of Sgr, both of which are poorly known. If, for example, there were originally $\sim$10 clusters associated with Sgr, then its luminosity must have been approximately twice that of Fornax for the same $S_N$. If Sgr had a more 'normal' $S_N$, it would have to be yet more luminous, considerably so if it was not a nucleated system (cf. Miller et al. 1998). Such relatively high luminosities ($M_V \approx -15$ or brighter), together with the luminosity – mean abundance relation for dE galaxies, would then be consistent with occurrence of quite metal-rich stars in this dE (e.g. Smecker-Hane & McWilliam 2002) and a relatively high mean abundance (cf. Cole 2001 and the references therein).

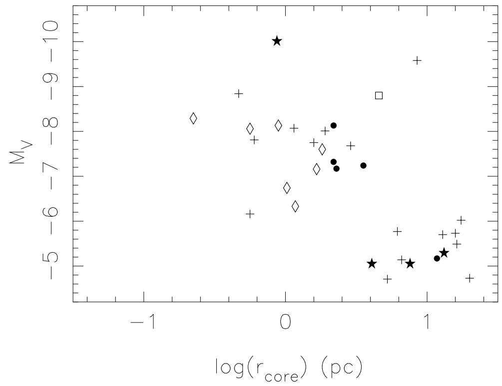


Figure 2. Globular cluster $M_V$ values as a function of core radius. Symbols as for the right panel of Fig. 1. Note that the NGC 205 GCS appears to lack low luminosity, large core radii clusters (which also have low central concentration, cf. Fig. 1). Such clusters may have been overlooked in current ground-based catalogs.

with $M_V \leq -8.0$ is comparable in the two samples: 0.27 for the combined dwarf GCS and 0.24 for the outer halo sample. Only in the fraction of faint clusters is there an apparent difference between the two systems: for the outer halo 56% of the clusters are fainter than $M_V = -6.2$, but for the combined dwarf GCS the figure is only 23 per cent. However, this difference may not be significant. The low luminosity clusters in the combined dwarf GCS come entirely from the Sgr and Fornax systems, while, as is apparent from Fig. 2, the NGC 205 GCS appears to lack such low central concentration, large core radius, low luminosity clusters. It is quite possible that such clusters have been overlooked in the existing ground-based surveys for globular clusters in this dwarf. This may well apply also to the other M31 dE companion GCS. Nevertheless, despite this apparent discrepancy, there is generally good agreement between the combined dwarf galaxy GCS and that of the outer halo as regards the distributions of surface brightness profile parameters and cluster luminosities.

### 3.2. Ages

Ages are best determined from measurements of main sequence turnoff luminosities but, at present, such measurements are only possible for clusters within ~140 kpc of the Galaxy; i.e. main sequence turnoff luminosities can be measured for the Fornax globular clusters, but not (yet) for globular clusters at the distance of M31. For the more distant clusters we have to rely on horizontal branch (HB) morphologies as a first order age indicator. All that can be said about the NGC 185 and NGC 205 clusters, and the WLM cluster, is that the HB morphologies are generally consistent with the metallicities (Geisler et al. 1999, Hodge et al. 2002). There is no indication of any "second parameter effect" and thus no obvious contradiction to the assumption that these clusters are similar in age to those of the Galactic halo.

For the nearer systems though, there is a much stronger result. Based on HST/WFPC2 data, it has been possible to establish that the oldest globular clusters in the solar neighbourhood, in the outer halo (e.g. NGC 2419 at $R_{GC} \approx$ 90 kpc), in the LMC, in Fornax, and in Sgr are coeval at the 1–2 Gyr (or better) level. In other words, regardless of the subsequent star formation histories, the very different locations, masses, densities, dark matter contents, etc, the initial epoch of star formation was apparently well synchronized across all components of the proto-Galactic halo. However, this result does not mean that all globular clusters in a given system have the same old age. Both Sgr and Fornax have at least one cluster that is significantly younger than the others, and the outer Galactic halo also contains a number of younger clusters.

In particular, Sgr has two clusters (Ter 7 and Arp 2), or three if Pal 12 is included, that are younger than the other two clusters M54 and Ter 8. In the case of Ter 7 the age difference is quite substantial (see Layden & Sarajedini 2000 and references therein). For Fornax, Buonanno et al. (1999) have recently shown that Fornax 4, which lies near the center of this dwarf, has an age that is ~3 Gyr younger than the other four clusters. Similarly, in the Galactic halo, the "younger" clusters include IC 4499, Pal 1, 3, 4 and 12, Eridanus and Ruprecht 106, and the age differences compared to the solar neighbourhood clusters are typically 2–3 Gyr.

These results clearly show that globular cluster formation can be on-going (at least for a few Gyr) in dwarfs like Sgr and Fornax. Given that when a dwarf is disrupted by the Galactic tidal field star and cluster formation is halted, then if the disruption of dwarfs is a significant contributor to the formation of the outer halo, the inference would be that the younger clusters now seen in the halo formed in dwarfs that were disrupted only at some time after the younger clusters formed. Equivalently, since clusters don't form in isolation, younger clusters can only occur in the halo if the disruption of the system in which they form doesn't occur until at least a few Gyr after the initial episode of star formation in the proto-Galactic halo. None of these comments are particularly new. After all, Searle & Zinn (1978) argued this was the case more than twenty years ago. What is new, however, is the confirmation of the existence of younger globular clusters in the non-disrupted dwarf galaxies in the outer Galactic halo.

### 3.3. Abundances

In general the mean abundance of the clusters in a GCS is lower than the mean abundance for the field population in the galaxy, and this is also true for the dwarf systems considered here. Using data available in the literature, the mean field star abundances for NGC 205, NGC 185, NGC 147, Fornax and Sgr are $\langle[\mathrm{Fe/H}]\rangle_{field} \approx$ –0.8, –1.2, –1.1, –1.2 and –1.0, respectively, while for the GCS (e.g. Da Costa & Mould 1988), the corresponding values are $\langle[\mathrm{Fe/H}]\rangle_{cluster} \approx$ –1.45 (6 clusters), –1.65 (5), –2.05 (2), –2.0 (5) and –1.6 (4; if Ter 7 is excluded, the value drops to –1.9). Further, in each dwarf not only is there a considerable abundance range within the field star population, but there is also a range in the abundances of the globular clusters, from approximately 0.4 dex in the Fornax GCS through perhaps as much as 1 dex or more (e.g. NGC 185, Sgr). Presumably the field – cluster mean abundance difference comes about because the globular clusters generally form early in the evolutionary life of the dwarf, perhaps in a characterisically turbulent initial star formation episode, while subsequent (perhaps more quiescent) star formation raises the mean abundance of

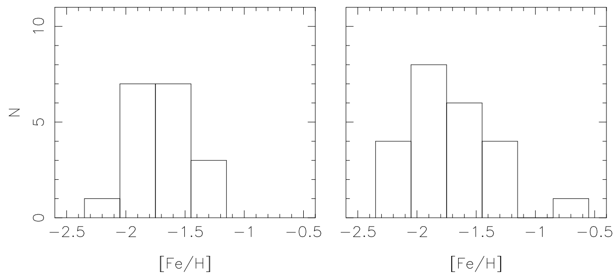


Figure 3. The *left panel* shows the abundance distribution for 18 Galactic halo globular clusters with $R_{GC} \geq 20$ kpc. The *right panel* shows the abundance distribution for 23 globular clusters associated with Local Group dwarf galaxies. The metal-rich object is the Sgr cluster Terzan 7.

the field stars without forming additional globular clusters. Certainly there is ample evidence that all the dwarfs considered here have had on-going star formation lasting at least a few Gyr.

Within the statistics of small samples, the GCS abundance distributions in each of the dwarfs appear to be unimodal in character, similar to the abundance distribution of the Galactic halo (as distinct from the disk/bulge) globular clusters. The sole exception to this is the Sgr system where the GCS abundance distribution is clearly bimodal – there are 3 metal-poor clusters (4 if NGC 5634 is included) and 1 (2 if Pal 12 is included) that is quite metal-rich. Both metal-rich clusters (Ter 7 and Pal 12) are considerably younger than the metal-poor clusters, but both fit the age-metallicity relation for the Sgr field stars as determined by Layden & Sarajedini (2000). In other words, Sgr apparently continued to form globular clusters and the younger clusters have the 'expected' abundance for their age. In this sense the cluster Fornax 4 is then somewhat anomalous – it is ∼3 Gyr younger than the other Fornax clusters but it is not notably different in abundance; indeed two of the older clusters have marginally higher abundances. Perhaps the evolution of Fornax did not result in a well-defined age-abundance relation as apparently applies in Sgr.

As regards the abundance distribution of the combined dwarf GCS, it is similar to that for the outer Galactic halo globular clusters, with the exception of the metal-rich cluster(s) in Sgr which have no counterpart in the outer halo, or indeed in any part of the halo except perhaps for Pal 1 at $R_{GC} \approx 17$ kpc. Rosenberg et al. (1998) list [Fe/H] ≈ –0.6 and an age between 6.3 and 8 Gyr for this cluster, which may, however, be a dynamically evolved old open cluster. The overall similarity between the two distributions is illustrated in the panels of Fig. 3: the mean for the outer Galactic halo clusters is $\langle[\mathrm{Fe/H}]\rangle \approx -1.67$ while the mean abundance for the combined dwarf GCS is $\langle[\mathrm{Fe/H}]\rangle \approx -1.80$ excluding Ter 7, and –1.75 with that cluster.

## 4. Summary

The material presented here clearly demonstrates that the globular cluster systems of existing local dwarf galaxies have properties that are consistent with the hypothesis that the disruption of similar dwarfs generated a sizeable fraction, if not all, of the globular clusters in the outer halo of the Galaxy. There is, however, a caveat associated with this hypothesis. The mean abundance of halo field stars is [Fe/H] $\approx -1.7$ (e.g. Ryan & Norris 1991), which is considerably less than the mean abundances of existing dwarfs like Fornax and Sgr. If we want to disrupt Fornax and Sgr-like systems to "acquire" their globular clusters, but at the same time avoid acquiring too many potential metal-rich halo stars, then the disruption necessarily has to be at fairly early epochs to prevent the dwarf from progressing very far in its chemical evolution. In terms of acquiring globular clusters, the alternative of disrupting more metal-poor dwarfs is not viable, as such systems are less luminous and therefore don't have globular cluster systems.

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