Globular clusters and the formation of the outer Galactic halo

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ABSTRACT

Globular clusters in the outer halo ($R_{gc} > 15$ kpc) are found to be systematically fainter than those at smaller Galactocentric distances. Within the outer halo the compact clusters with half-light radii $R_h < 10$ pc are only found at $R_{gc} < 40$ kpc, while on the other hand the larger clusters with $R_h > 10$ pc are encountered at all Galactocentric distances. Among the compact clusters with $R_h < 10$ pc that have $R_{gc} > 15$ kpc, there are two objects with surprisingly high metallicities. One of these is Terzan 7, which is a companion of the Sagittarius dwarf. The other is Palomar 1. The data on these two objects suggests that they might have had similar evolutionary histories. It is also noted that, with one exception, luminous globular clusters in the outer halo are all compact whereas faint ones may have any radius. This also holds for globular clusters in the LMC, SMC and Fornax dwarf. The lone exception is the large luminous globular NGC 2419. Possibly this object is not a normal globular cluster, but the stripped core of a former dwarf spheroidal. In this respect it may resemble ω Centauri.

Key words: Galaxy: halo, formation – globular clusters: general – Magellanic Clouds

1 INTRODUCTION

Between 1962 and 1977 it was generally believed that the Galaxy had formed by rapid dissipative collapse of a single massive proto-Galaxy. Faith in this paradigm was severely shaken by two papers presented at the 1977 Yale conference on The Evolution of Galaxies and Stellar Populations (Tinsley & Larson 1977). In one of these Searle (1977) showed that, contrary to expectations from the Eggen, Lynden-Bell & Sandage (1962) (= ELS) model, globular clusters in the outer halo of the Galaxy did not exhibit a metallicity gradient (although we note that it is not necessarily expected that a radial abundance gradient be set up in the very outer part of the Galaxy if the initial phase of the ELS collapse is in free-fall (Sandage 1990)). Furthermore Toomre (1977) pointed out that “It seems almost inconceivable that there wasn’t a great deal of merging of sizable bits and pieces (including quite a few lesser galaxies) early in the career of every major galaxy”. These ideas were elaborated upon by Searle & Zinn (1978) (= SZ) who argued that the lack of an abundance gradient in the outer Galactic halo, along with anomalies in the colour-magnitude diagrams of outer halo clusters suggested that the outer Galactic halo was assembled over an extended duration via the infall of transient proto-Galactic fragments. Zinn (1980) describes this process of accretion of proto-Galactic gas clouds in more detail: “The clouds in the central zone [of the Galaxy] merged to form a large gas cloud that later evolved into the Galactic disk. The clouds in the second zone evolved as isolated systems for various lengths of time up to ~ 5 Gyr, but eventually all of these clouds collided with the disk and were destroyed. The clouds of the outermost zone have evolved in relative isolation until the present time and have become the Magellanic Clouds and the dwarf spheroidal galaxies”. For additional detailed information the reader is referred to van den Bergh (1995; 2004).

Presently available data appear to favour the view that the main body of the Milky Way system, i.e. the region with $R_{gc} < 10$ kpc, was formed more-or-less à la ELS (as modified by Sandage (1990)), whereas the region with $R_{gc} > 15$ kpc was probably mainly assembled by infall and capture of lesser fragments as envisioned in the SZ model. Zinn (1993) first pointed out that the observed data for the halo globular clusters was best explained in terms of both ELS and SZ. He split the halo globular clusters into two groups according to their horizontal branch morphologies. The properties of Zinn’s “old halo” (blue horizontal branch) sub-system are consistent with the majority of its members having been formed as part of an ELS-type collapse, while the properties of his “young halo” (red horizontal branch, or second parameter) sub-system are more in line with its members having been formed in ancestral fragments and accreted into the outer halo at later epochs. Additional support for this view is provided by the observation (van den Bergh 1993) that a significant fraction of the globular clusters at $R_{gc} > 15$ kpc are on plunging orbits, and that a number of outer halo objects with relatively well-determined orbits have retrograde motions (Dinescu et al. 1999). It is noted in passing (van den Bergh 1995) that cluster metallicity appears to correlate more strongly with the perigalactic distances of globular clusters than it does with the present Galactic distance $R_{gc}$. 

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Table 1. Globular clusters with $R_{gc} > 15$ kpc

| Name     | $R_{gc}$ (kpc) | $M_V$   | [Fe/H] | $R_h$ (pc) |
|----------|---------------|---------|--------|------------|
| NGC 1261 | 18.2          | −7.81   | −1.35  | 3.6        |
| Pal. 1   | 17.0          | −2.47   | −0.60  | 2.2        |
| AM 1     | 123.2         | −4.71   | −1.80  | 17.7       |
| Eridanus | 95.2          | −5.14   | −1.46  | 10.5       |
| Pal. 2   | 35.4*         | −8.01   | −1.30  | 5.4        |
| NGC 1851 | 16.7*         | −8.33   | −1.22  | 1.8        |
| NGC 1904 | 18.8*         | −7.86   | −1.57  | 3.0        |
| NGC 2298 | 15.7*         | −6.30   | −1.85  | 2.4        |
| NGC 2419 | 91.5          | −9.58   | −2.12  | 17.9       |
| NGC 2808 | 11.1+         | −9.39   | −1.15  | 2.1        |
| Pyxis    | 41.7          | −5.75   | −1.30  | 15.6       |
| Pal. 3   | 95.9          | −5.70   | −1.66  | 17.8       |
| Pal. 4   | 111.8         | −6.02   | −1.48  | 17.2       |
| NGC 4147 | 21.3*         | −6.16   | −1.83  | 2.4        |
| Rup. 106 | 18.5          | −6.35   | −1.67  | 6.8        |
| NGC 5024 | 18.3          | −8.70   | −1.99  | 5.7        |
| NGC 5053 | 16.9          | −6.72   | −2.29  | 16.7       |
| AM 4     | 25.5          | −1.60   | −2.00  | 3.7        |
| NGC 5466 | 16.2          | −6.96   | −2.22  | 10.4       |
| NGC 5634 | 21.2          | −7.69   | −1.88  | 4.0        |
| NGC 5694 | 29.1          | −7.81   | −1.86  | 3.3        |
| IC 4499  | 15.7          | −7.33   | −1.60  | 8.2        |
| NGC 5824 | 25.8          | −8.84   | −1.85  | 3.4        |
| Pal. 5   | 18.6          | −5.17   | −1.41  | 20.0       |
| Pal. 14  | 69.0          | −4.73   | −1.52  | 24.7       |
| NGC 6229 | 29.7          | −8.05   | −1.43  | 3.3        |
| Pal. 15  | 37.9          | −5.49   | −1.90  | 15.7       |
| IC 1257  | 17.9          | −6.15   | −1.70  | ...        |
| NGC 6715 | 19.2*         | −10.01  | −1.58  | 3.8        |
| Ter. 7   | 16.0*         | −5.05   | −0.58  | 2.6        |
| Arp 2    | 21.4*         | −5.29   | −1.76  | 15.9       |
| Ter. 8   | 19.1*         | −5.05   | −2.00  | 7.6        |
| NGC 7006 | 38.8          | −7.68   | −1.63  | 4.6        |
| Pal. 12  | 15.9*         | −4.48   | −0.94  | 7.1        |
| Pal. 13  | 26.7          | −3.74   | −1.74  | 3.5        |
| NGC 7492 | 24.9          | −5.77   | −1.51  | 9.2        |

* Probably associated with the Sagittarius dwarf.
† Possibly associated with the disrupted Canis Major dwarf.
‡ NGC 2808 is included in this Table even though it has $R_{gc} < 15$ kpc, because of its possible association with the Canis Major dwarf.

2 GLOBULAR CLUSTERS IN THE OUTER GALACTIC HALO

In the present paper we use data in the recent compilation by Harris (1996) (2003 update) to study some of the properties of the globular clusters in the outer halo ($R_{gc} > 15$ kpc) in an attempt to find out more about how the outer Galactic halo was assembled. Not all galaxies are formed in the same way. Whereas the main body of our own Milky Way system seems to have formed via the early collapse of a single large protogalaxy the Andromeda galaxy (M31) appears to have been assembled at a later date via the merger of at least two major ancestral fragments (Freeman 1999; van den Bergh 2004; Brown 2004).

The Harris catalog contains 35 Galactic clusters with $R_{gc} > 15$ kpc. Data on these clusters are listed in Table 1. In this Table we have also included data for NGC 2808, which has $R_{gc} = 11.1$ kpc, because of its possible association with the Canis Major dwarf (see below). Of the 35 objects with $R_{gc} > 15$ kpc, the following seven appear to be associated with the Sagittarius dwarf galaxy: M54, Terzan 7 and 8, and Arp 2 (Ibata et al. 1994; Da Costa & Armandroff 1995); Pal. 12 and NGC 4147 (Dinescu et al. 2000; Martínez-Delgado et al. 2002; Bellazzini et al. 2003a); and Pal. 2 (Majewski et al. 2004). Also note the possible physical association of the globular clusters NGC 1851, NGC 1904, NGC 2298 and NGC 2808, plus a number of old open clusters, with the recently discovered Canis Major dwarf (Martin et al. 2004; Bellazzini et al. 2003b; Frinchaboy et al. 2004). In particular, Bellazzini et al. (2003b) find strong evidence that the clusters AM 2 and Tombaugh 2 [which are not cataloged as globulars by Harris] are associated with the Canis Major system. In fact, these authors suggest that Tombaugh 2 may actually represent an over-density in the CMA field itself, similar to those observed in the Sagittarius and Ursa Minor dwarf galaxies. Finally, Carraro et al. (2004) have shown that the cluster Berkeley 29 is associated with the Monoceros stream, which is thought (Martin et al. 2004) to be part of the disrupted CMA dwarf. However, this cluster has an age of $\sim 5$ Gyr, which makes it somewhat too young to be of interest for the present study of globular clusters.

Information on the globular clusters in the LMC, the SMC, and the Fornax dwarf spheroidal is collected in Table 2 using the data from Mackey & Gilmore (2003a; 2003b; 2003c). The total luminosities and half-light radii in this Table have been newly derived for the present work. The total luminosities ($M_V$) were obtained by integrating these authors’ radial brightness profiles to appropriate limiting radii (~ 50 pc) using Eq. 12 of Mackey & Gilmore (2003a). Rearranging this equation then allows the subsequent determination of the half-light radii. Distance moduli of 18.50, 18.90, and 20.68 have been adopted for the LMC, SMC, and Fornax systems, respectively.

The LMC sample of Mackey & Gilmore (2003a) omits four known globulars (NGC 1928, 1939, Reiculium, and ESO121-SC03). A recent Hubble Space Telescope program has obtained images of these four objects using the Advanced Camera for Surveys (e.g., Mackey & Gilmore 2004). Preliminary radial luminosity profiles (for which details will follow in a future work – Mackey & Gilmore, in prep.) have allowed integrated magnitudes and half light radii to be estimated for these four clusters; however those for NGC 1928 and 1939 are very uncertain due to severe crowding in the cluster images. Half light radii for these two objects should be considered upper limits only.

The LMC cluster sample is therefore complete, consisting of all 16 known globular cluster-type objects. The Fornax cluster sample is also complete (5 clusters). For the SMC, we have only listed NGC 121. Although there are other reasonably old clusters in this galaxy (e.g., Kron 3, Lindsay 1), it is not clear that they are directly comparable to the global clusters in the Galactic halo.

It is the aim of the present paper to see if such data on the globular clusters in nearby dwarf galaxies can provide us with hints about the evolutionary history of the outer regions of our own Milky Way system.

2.1 The luminosities of outer halo globular clusters

It has been known for many years (e.g. van den Bergh 2000) that globular clusters in the outer halo of the Galaxy are, on average, fainter than those in the inner halo. This effect is shown in Figure 1. A Kolmogorov-Smirnov test shows that there is only a 0.4 per cent probability that the $M_V$ values of the 35 globulars with $R_{gc} > 15$ kpc and the 111 globulars having $R_{gc} < 15$ kpc listed in the

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updated version of Harris (1996) were drawn from the same parent luminosity distribution.

This difference in luminosity between clusters at large and small values of $R_{gc}$ is, at least in part, due to the fact that globulars at large $R_{gc}$ values are less likely to have been destroyed by bulge shocks (Aguilar, Hut & Ostriker 1988) and tidal stresses (Surdin 1994) than clusters at smaller Galactocentric distances. It is noted in passing that a Kolmogorov-Smirnov test shows no statistically significant difference between the luminosity distribution of the seven clusters likely to be associated with the Sagittarius dwarf and that of the other 28 clusters at $R_{gc} \geq 15$ kpc. This is exactly what one would expect if the Galactic outer halo globular clusters had originally all been associated with dwarf spheroidal galaxies—most of which have since been destroyed. We point out, however, that the number of clusters involved is too small to attach great significance to this result.

Similarly, it is interesting to note that the four clusters which have been suggested as members of the disrupted Canis Major dwarf are, on average, more luminous than the seven Sagittarius clusters and five Fornax clusters listed in Tables 1 and 2. However, both the difference and the number of clusters concerned are too small to constitute a convincing argument against the notion that these four clusters were originally formed in a dSph-type galaxy.

It is also of interest to note that there is, perhaps, a hint of a relationship between luminosity and galactocentric radius among the globular clusters in the Large Magellanic Cloud. All 13 LMC clusters with $R_{LMC} < 10^3$ are brighter than $M_V = -6.0$. On the other hand two of the three Large Cloud clusters with $R_{LMC} \geq 10^3$ are fainter than $M_V = -6.0$.

The existence of a metallicity gradient for globulars with $4 < R_{gc} < 10$ kpc, and the absence of such a gradient for globular clusters with $R_{gc} > 10$ kpc are consistent with the view (e.g. van den Bergh 2004) that the inner region of the Milky Way system formed by a collapse of the type envisioned by Eggen, Lynden-Bell & Sandage (1962), whereas the outer part of our Galaxy was mainly assembled by capture of bits and pieces in the manner suggested by Searle & Zinn (1978).

2.2 Radial luminosity dependence of globular clusters in the Galactic halo

A comparison between the luminosity distributions of globular clusters with $R_{gc} < 15$ kpc and those with $15 \leq R_{gc} < 25$ kpc, as depicted in Figure 2, shows a tendency for the more distant cluster sample to be less luminous than the the inner sample. However, a Kolmogorov-Smirnov test shows that this difference is only significant at the 90 per cent level. The difference between the luminosity distributions of the globular clusters with $R_{gc} < 15$ kpc and those with $R_{gc} \geq 25$ kpc is, however, much more striking, with faint clusters being deficient in the sample with small $R_{gc}$.

A Kolmogorov-Smirnov test shows that there is only a 1.5 per cent probability that the samples with $R_{gc} < 15$ kpc and with $R_{gc} \geq 25$ kpc were drawn from the same parent population of cluster luminosities.

The most striking difference is seen between the clusters at $R_{gc} \geq 50$ kpc and those at smaller Galactocentric radii. In this most distant sample only one cluster (NGC 2419) is brighter than $M_V = -6.1$. Perhaps the latter object is, like NGC 6715 = M54 (e.g., Layden & Sarajedini 2000) and ω Centauri (see e.g., Bekki & Freeman 2003; Tsuchiya et al. 2003, and references therein), the stripped remnant of the core of a former dwarf spheroidal companion to the Galaxy. If this hypothesis is correct one might expect to observe a significant scatter in the metallicities of stars on the giant branch of NGC 2419. However, the rather thinly populated
Figure 2. Luminosity distributions of Galactic globular clusters with $R_{gc} < 15$ kpc (upper left) and with $15 \leq R_{gc} < 25$ kpc (upper right); $R_{gc} \geq 25$ kpc (lower left); and $R_{gc} \geq 50$ kpc (lower right). The samples appear systematically less luminous at greater Galactocentric radii.

Figure 3. Half-light radius $R_h$ versus Galactocentric distance $R_{gc}$ for Galactic globular clusters with $R_{gc} > 15$ kpc (dots). Also plotted are the globular clusters associated with the Sagittarius dwarf galaxy (x marks). The figure shows that compact clusters do not occur at $R_{gc} > 40$ kpc.

color-magnitude diagram of NGC 2419 published by Harris et al. (1997) appears to show no evidence for such a scatter in metallicity. The apparent absence of such scatter in the color-magnitude diagram of NGC 2419 might be due to the fact that both the core and the spheroidal envelope of this object consist of very metal-poor stars. In other words the parent galaxy of NGC 2419 might, like the Ursa Minor dwarf, have produced only a single generation of quite metal-poor stars.

2.3 Half-light radii of outer halo globular clusters

Figure 3 shows a plot of the dependence of the cluster half-light radius $R_h$, which does not change much due to dynamical evolution (Spitzer & Thuan 1972; Lightman & Shapiro 1978; Murphy, Cohn & Hut 1990), on Galactocentric distance $R_{gc}$. The figure shows that compact clusters (defined as objects having $R_h < 10$ pc) only occur at $R_{gc} < 15$ kpc, whereas more extended clusters with $R_h > 10$ pc are found to be located at all radii. However, it seems likely that a few very extended clusters at relatively small Galactocentric distances, such as NGC 5053, might actually be outer halo clusters that are presently orbiting closer to the Galactic center. Odenkirchen et al. (2003) have shown that the outer halo cluster Pal. 5 is very close to complete tidal disruption, a fact which might help explain its large half-light radius. We note that it is not clear whether Pal. 5 has a large radius entirely because of tidal effects, or was it actually a large initial radius that allowed tidal effects to become important. The most extended globular presently known is Pal. 14 = AvdB, which has a half-light radius of 24.7 pc. It is of interest to note that the cluster Arp 2, which appears to be associated with the Sagittarius system, has a large half-light radius $R_h = 15.9$ kpc, but that the other globulars associated with the Sagittarius system are all compact.

It is of interest to point out that Forbes, Strader & Brodie (2004), in their study of the prospective cluster systems of the Canis Major and Sagittarius dwarf galaxies, found that the four CMa clusters (NGC 1851, 1904, 2298, and 2808) have unusually small radii for their Galactocentric distance.

It has been known for many years (e.g. van den Bergh & Mor- bey 1984) that the half-light radii of Galactic globular clusters grow with increasing Galactocentric distance. By the same token it has long been known (Hodge 1962) that old clusters near the core of the LMC are generally more compact than are clusters at larger distances from the center of the Large Cloud. Using our new data on cluster half-light radii this effect is clearly shown in Figure 4. This Figure shows that the majority of those clusters close to the rotation centre of the LMC are compact, while those at large distances are much more extended. The largest LMC cluster, Reticulum, is one of the most distant; while the most distant cluster, NGC 1841, is one of the most extended. The clusters NGC 1898 and Hodge 11 are larger than might be expected given their comparatively small distances from the LMC centre. These objects are possibly LMC halo clusters projected on the inner parts of this galaxy.

Finally, we note that extended globular clusters have a luminosity function which differs strongly from that of more compact globular clusters (e.g., van den Bergh (1982)). It seems likely that this is related to the observed correlations between cluster luminosity and Galactocentric radius (see the previous Section), and cluster size and and Galactocentric radius (this Section).

2.4 Metallicity and cluster size

A plot of half-light radius $R_h$ versus metallicity $[\text{Fe/H}]$ is shown in Figure 5. Most of the globular clusters associated with the Sagittarius dwarf (Ibata et al. 1994; Forbes et al. 2004), which are plotted as crosses in Fig. 5, have small $R_h$ values. However the large cluster Arp 2, with $R_h = 15.9$ pc, is an exception to this rule. Among the
clusters with $R_{gc} > 15$ kpc there are two that are surprisingly metal rich. One of these is Terzan 7, which is believed to be associated with the Sagittarius dwarf, whereas the other (Palomar 1) appears to be an isolated object. Nevertheless the unusually high metallicities of these two objects suggest that they could have had similar evolutionary histories, i.e. Pal. 1 might once have been associated with a dwarf spheroidal galaxy that was subsequently destroyed by tidal forces. It is also noted that the cluster Palomar 12, which is associated with the Sagittarius dwarf, occurs close to the region of the $R_h$ vs. $[Fe/H]$ diagram in which Ter. 7 and Pal. 1 are located.

Finally (and not unexpectedly) the most distended outer halo clusters generally have lower metallicities than the more compact objects that typically inhabit the zone with small $R_{gc}$ values.

2.5 Cluster radius and cluster luminosity

Figure 6 shows that the halo globular clusters with $R_h > 15$ kpc do not fill the $R_h$ vs $M_V$ plane uniformly. No clusters, except NGC 2419, lie above the relation

$$\log R_h = 0.2M_V + 2.6. \quad (1)$$

The figure shows that a compact halo globular cluster can have any luminosity, while large globular clusters in the outer halo can only be intrinsically faint. Furthermore, the most luminous globular clusters tend to be among the most compact. The only exception to this rule is NGC 2419. As noted in Section 2.2, it is possible that this large luminous object is actually the surviving core of a dwarf spheroidal galaxy, rather than a normal globular cluster. The atypical inner halo cluster $\omega$ Centauri is also marked on Figure 6. Like NGC 2419, it lies significantly above the line defined by Eq. 1. There are many suggestions in the literature (see e.g., Bekki & Freeman 2003, and the references therein) that $\omega$ Centauri is the remaining core of a now disrupted dwarf galaxy. The position of this

Figure 4. Half-light radius $R_h$ versus $R_{LMC}$, the angular distance from the rotation centre of the LMC, for 16 globular clusters in the Large Cloud. We calculate $R_{LMC}$ relative to the LMC rotation centre at $\alpha = 05^h 20^m 40^s$, $\delta = -69^\circ 14' 12''$ (J2000.0).

Figure 5. Half-light radius $R_h$ versus metallicity $[Fe/H]$. The proximity of Ter. 7 and Pal. 1 suggests that these objects might have had similar evolutionary histories. Pal. 12 also falls close to these two objects. Galactic halo clusters are shown as dots and Sagittarius globulars as crosses.

Figure 6. Half-light radius $R_h$ versus luminosity $M_V$ of globular clusters with $R_{gc} > 15$ kpc. The figure shows that all outer globulars, except NGC 2419, lie below the relation given by Eq. 1 which is shown as a slanting line in the Figure. $\omega$ Centauri (plotted as a star) also lies significantly above this relation. Clusters associated with the Sagittarius dwarf are shown as crosses.
Figure 7. Half-light radius $R_{h}$ versus luminosity $M_V$ for globular clusters associated with the LMC (filled squares), the SMC (star) and Fornax dwarf (open triangles). Together with Figure 6, this plot shows that the globular clusters in the outer Galactic halo having $R_{gc} > 15$ kpc occupy the same region in the diagram as do the globular clusters in the LMC, the SMC, and the Fornax and Sagittarius dwarfs. The “faint fuzzies” of Larsen & Brodie (2000) lie above and to the right of the two dotted lines (Brodie & Larsen 2003). This shows that, in purely structural terms, these objects are not dissimilar to the most extended clusters in the outer Galactic halo and nearby dwarf galaxies.

cluster in Figure 6 adds plausibility to our suggestion that NGC 2419 is of a similar nature.

It is noted in passing that the globular clusters associated with the Sagittarius dwarf, which are plotted as crosses in Figure 6, appear to be distributed similarly to other globular clusters at $R_{gc} > 15$ kpc.

Figure 7 shows a plot of the distribution of the globular clusters in the LMC, the SMC and the Fornax dwarf in the $R_{h}$ vs. $M_V$ plane. This figure shows that these external globular clusters also fall below the line defined by Eq. 1, inhabiting a comparable region of the plane to that occupied by the globular clusters in the outer Galactic halo. The LMC Reticulum cluster is the most extended object in the external sample, with $R_{h} = 19.3$ pc. The resemblance between the external globular clusters and those in the outer Galactic halo may suggest a similar origin – i.e., in dwarf spheroidal-like galaxies.

It is presently not clear why the most luminous, and hence presumably most massive, globular clusters have the smallest radii. This conclusion appears to hold true both for Galactic globular clusters and for those associated with the Magellanic Clouds and the dwarf spheroidal companions of the Milky Way. It is noted that in the case of a constant cluster mass-to-light ratio, Eq. 1 implies that the upper limit to globular cluster sizes in the outer halo (excluding NGC 2419) is defined by

$$M R_{h}^{2} = \text{const},$$

where $M$ is cluster mass. In form, this is perhaps reminiscent to the correlation $R_{h} \propto M^{-0.63}$ noted by Ostriker & Gnedin (1997) for clusters with $5 < R_{gc} < 60$ kpc. The majority of clusters in Figures 6 and 7 appear to follow a similar correlation, running approximately parallel to the line defined by Eq. 1.

McLaughlin (2000) defines a fundamental plane for globular clusters using observations of clusters at all Galactocentric radii. Although he only finds a very weak correlation between luminosity (mass) and half-light radius, it seems plausible that the cut-off we observe in the present work is related to the presence of a fundamental plane for globular clusters. McLaughlin argues that the characteristics of the fundamental plane were set by the cluster formation process. The fact that NGC 2419 and $\omega$ Centauri fall above our cut-off and away from all other globular clusters seems likely to place them away from the fundamental plane. If this hypothesis is correct then it would imply a formation scenario for NGC 2419 and $\omega$ Centauri different from that for the rest of the Galactic globular clusters. One such scenario is that these two objects are not true globular clusters, but rather the remaining cores of now defunct dwarf galaxies.

Finally, it is informative to place the “faint fuzzy” clusters discovered in the lenticular galaxies NGC 1023 and 3384 by Larsen & Brodie (2000) and Larsen et al. (2001) on our log $R_{h}$ vs. $M_V$ plot. In their Figures 1 and 2, Brodie & Larsen (2003) show that the faint fuzzies have $R_{h} \geq 7$ pc and integrated luminosities fainter than $M_V = -7.5$. These define a region on our Figure 7, marked by two dotted lines. The position of this region shows that while the faint fuzzies are clearly very distinct from any globular clusters in the local neighbourhood in terms of their composition and spatial and kinematic properties (Brodie & Larsen 2003), they are not so dissimilar purely in terms of luminosity and structure to the most extended clusters in the outer Galactic halo and nearby dwarf galaxies. It would be important to know if any of the largest faint fuzzies lie above our Eq. 1, as appears possible from Figure 7.

3 CONCLUSIONS

Presently available observations appear to be consistent with the hypothesis that the globular clusters in the outer ($R_{gc} > 15$ kpc) Galactic halo were once all associated with dwarf spheroidal-like fragments that have since disintegrated. On the other hand the majority of inner halo globular clusters with $R_{gc} < 10$ kpc were probably formed in association with the main body of the Milky Way system. The fact that the sample of outer halo globulars contains more faint clusters than the inner halo is likely due to the destruction of low-mass inner clusters by disk shocks and tidal stripping. By the same token the scarcity of large globulars at small $R_{gc}$ values is likely also due to such destructive forces.

The presence of a few quite metal-rich clusters, such as Terzan 7 ([Fe/H] = -0.58) and Palomar 1 ([Fe/H] = -0.60), and perhaps Palomar 12 ([Fe/H] = -0.98) at quite large Galactocentric radii appears anomalous. The existence of such metal-rich objects in the outer Galactic halo can be explained if they formed in, or in association with, dwarf spheroidal galaxies (as appears likely for Ter. 7 and Pal. 12). With one exception, luminous globular clusters in the outer halo are all compact whereas faint ones may have any radius, a result which also holds for globular clusters in the LMC, SMC and Fornax dwarf spheroidal. We speculate that the luminous ($M_V = -9.58$) and very large ($R_{h} = 17.9$ pc) cluster NGC 2419, which is located at a Galactocentric distance of 91.5 kpc, might be the remnant core of a now dispersed dwarf spheroidal galaxy. Apart
from apparently not possessing an internal metallicity spread, its properties are similar to the very large and luminous globular cluster ω Centauri, which might also be such a stripped core of a former dwarf spheroidal galaxy.

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