GLOBULAR CLUSTERS AND THE FORMATION OF THE GALACTIC HALO

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Abstract.

The radii of globular clusters are used to study the early evolution of the Galactic halo. It is found that such cluster radii increase with Galactocentric distance and depend on orbit shape. It is suggested that metal enrichment in the Galactic halo might have been mainly a local phenomenon, whereas cluster radii may have been determined by more global properties of the protogalaxy.

1. Introduction

Present ideas on the formation of the Galaxy and the evolution of the halo were largely shaped by the pioneering papers of Eggen, Lynden-Bell and Sandage (1962) and Searle & Zinn (1978), which will subsequently be referred to as ELS and S&Z. On the ELS picture the entire Galactic halo collapsed rapidly; in which the exact meaning of "rapidly" is explained by Sandage (1990). On the other hand Searle (1977) and S&Z envisage a situation in which halo globular clusters form within a number of more or less isolated fragments before, or during, the initial phases of Galactic collapse. In the S&Z scenario gas masses, clusters and stars of the outer halo continued to fall into the Galaxy for some time after the collapse of its central regions had been completed. The development of this model was influenced by (but not entirely driven by) the discovery that *the globular clusters with R_{gc} > 10 kpc do not exhibit a radial abundance gradient.*

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2. Cluster Radii Versus Galactocentric distance

N-body calculations by Spitzer & Thuan (1972), Lightman & Shapiro (1978) and Murphy, Cohn & Hut (1990) show that the half-light radii $r_h$of globular clusters change little over periods as long as 10 relaxation times. For many globulars $r_h$therefore provides information on conditions at the time of cluster formation. Fig. 1 shows a plot of $r_h$versus R_{gc} from data recently compiled by Djorgovski (1993). The figure shows that $r_h$for Galactic globulars grows with increasing Galactocentric distance, and that $r_h \propto R_{gc}{}^{\gamma}$, with $\gamma \approx 2/3$. A similar relation is found for the clusters associated with the Large Magellanic Cloud (van den Bergh 1994). The absence of very extended clusters at small values of R_{gc} might be partly due to destruction of such large objects by Galactic tidal forces. However, the present absence of compact clusters in the outer Galactic halo must be due to the fact that such objects never formed. In other words the data plotted in Fig. 1 suggest that *the Galaxy exhibits a real radial gradient in the dimensions of globular clusters located at R_{gc} > 10 kpc.* Fig. 1 also shows that clusters with a wide range in metallicity follow similar mean relations between r_h and R_{gc}. The existence of such a relationship, between cluster properties and distance from the Galactic center, is surprising and appears difficult to reconcile with the S&Z picture, in which the properties of halo "fragments" are not expected to depend on their distance from the center of the Galaxy.

Searle (1977) assumes "complete mixing within fragments and no mixing between them". This makes it improbable that proto dwarf spheroidal galaxies should be identified with Searle's fragments. This is so because individual stars within dwarf spheroidals often exhibit a wide range in metallicity. Furthermore van den Bergh (1994) finds that the globular clusters in the Fornax dwarf galaxy have $<r_h> = 3.2$ pc, whereas globular clusters in the outer halo of the Galaxy are much larger having $r_h > 10$ pc. It therefore appears safe to conclude that the globular clusters in the outer halo of the Galaxy did *not* form in "fragments" that resembled proto dwarf spheroidals. This line of reasoning is also supported by the observation that giant carbon stars are rather rare in the Galactic halo (Green *et al.* 1994), but quite common in dwarf spheroidals (Azzorpardi & Lequeux 1992). Van den Bergh (1994) also finds that the majority of the true globular clusters associated with the LMC have $r_h < 10$ pc, and therefore differ from globulars in the outer halo of the Galaxy. This indicates that Searle's "fragments" cannot be identified with objects resembling the proto LMC.

Fig. 2 shows the mean surface brightness of Galactic globular clusters within r_h, as a function of distance from the Galactic center. This figure also appears to show a radial gradient beyond R_{gc}= 10 kpc. Compact clusters with a high central surface brightness are expected to survive preferentially

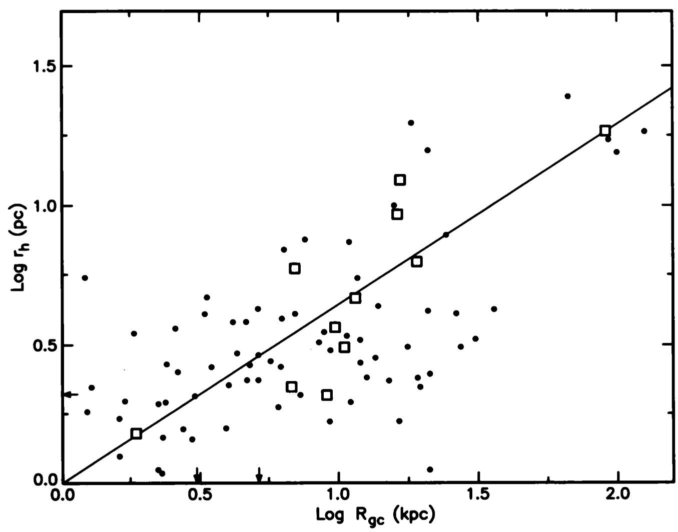

Figure 1. Cluster radius versus Galactocentric distance for globular clusters with -2.0 < [Fe/H] < -1.0 (dots) and [Fe/H] < -2.0 (squares). The fiducial line is the relation log r_h(pc) = 0.65 log R_{gc}(kpc). Clusters in both metallicity ranges appear to scatter about the same r_h versus R_{gc} relation.

in the outer halo. Their absence indicates that such objects were probably never formed in the outer halo of the Galaxy. Figs. 1 and 2 therefore suggest that *the properties of globular clusters, and hence of the "fragments" from which they formed, were a function of Galactocentric distance.*

It is curious that the globular cluster radii at $R_{gc} > R_{\odot}$ appear to exhibit a radial gradient, while cluster metallicities do not (Searle & Zinn 1978). This conundrum could, perhaps, be resolved by assuming that *metal enrichment in the Galactic halo was predominantly a local phenomenon, whereas cluster radii might have been mainly determined by global properties of the halo of the protoGalaxy.* Powerful UV radiation from a central source might be an example of a phenomenon that would produce mainly global, rather than local, effects.

3. Cluster Radii Versus Orbital Characteristics

Fig. 3 shows a plot of r_h versus R_{gc} for all globular clusters for which this information is given in Djorgovski (1993). The figure shows that clusters on circular orbits (van den Bergh 1993) have systematically larger radii than do other clusters at similar Galactocentric distances. A Kolmogorov-Smirnov test shows that the probability of the clusters in circular orbits

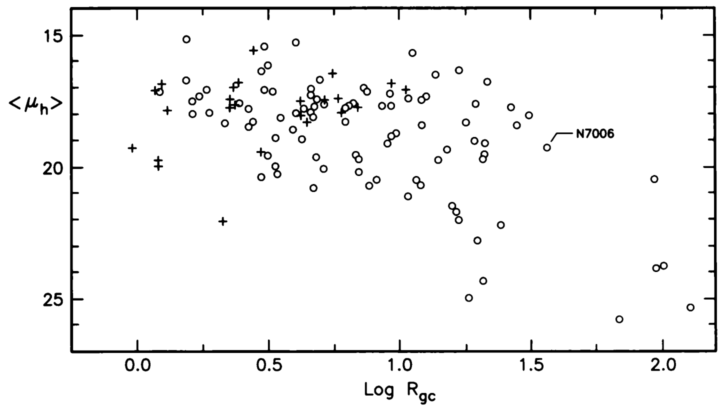

Figure 2. Average surface brightness (corrected for absorption) ¡h¿o, within the half-light radius r_h, versus Galactocentric distance R_{gc}. Clusters with collapsed cores are shown as crosses. Note the absence of high surface brightness clusters at large distances from the Galaxy.

having been drawn from the same parent population of distances from the fiducial line, as the other clusters in Fig. 3, is $< 1\%$. Globulars on circular, or nearly circular, orbits probably have above-average values of r_h because their orbits avoid the dense central regions of the Galaxy where clusters on more elongated orbits have their outer regions trimmed by tidal forces.

Fig. 4 shows that clusters on retrograde orbits (van den Bergh 1993) are, on average, smaller than other globulars. This difference might be due to the fact that many clusters on retrograde orbits dip deeply into the Galaxy, where tidal forces will trim off their envelopes. *Alternatively ram-pressure stripping of gaseous proto globular clusters might have preferentially removed the outer regions of retrograde objects moving through a (mostly prograde) gaseous halo.* On the latter hypothesis (Stetson 1994) one might have expected clusters on retrograde orbits to be fainter than globulars on prograde orbits. This is *not* observed to be the case. For 11 retrograde clusters

$< M_V >= -7.40 \pm 0.25$, compared to $< M_V >= -6.95 \pm 0.63$ for 12 clusters on prograde orbits. A third possibility is that some of the metal-poor clusters in retrograde orbits originally formed in dwarf spheroidal galaxies that were captured into retrograde orbits.

Available observations hint at the possibility that the youngest halo clusters [the α Population of van den Bergh (1993)] may be systematically smaller than other (mostly older) halo globular clusters at similar Galactocentric distances.

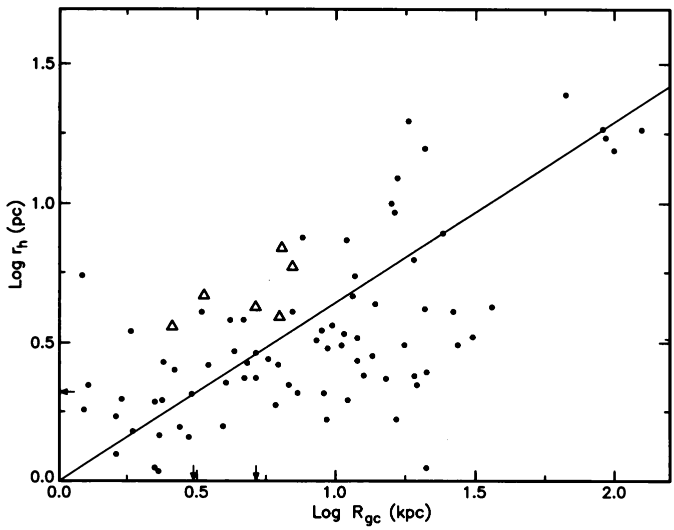

Figure 3. Metal-poor clusters on circular orbits (triangles), are seen to have above-average radii.

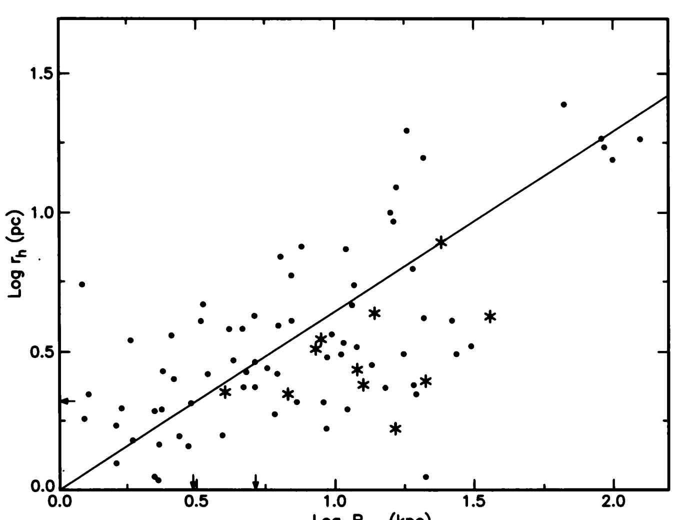

Figure 4. Clusters on retrograde orbits (asterisks) appear to have below-average radii and fall below the mean relation between r_h and R_{gc}.

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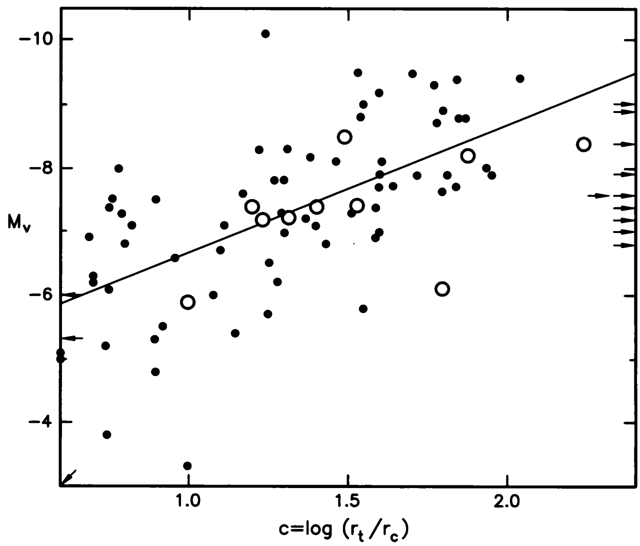

Figure 5. Relation between cluster luminosity MV and central concentration c = log (r_t/r_c). Clusters with collapsed cores, shown as arrows, do not follow this relation. Globulars on retrograde orbits (open circles) are seen to fall close to, or slightly below, the mean relation given by Eqn.(1).

4. Relation Between Structure and Luminosity of Globular Clusters

It was first pointed out by Shapley & Sawyer (1927) that the central concentration of light in globular clusters correlates with luminosity. Fig. 5 shows this same relationship using modern data compiled by Djorgovski (1993). The figure shows that, for clusters which do not have collapsed cores,

$$M_V \sim -4.7 - 2\log(r_t/r_c), \qquad 1$$

in which r_t and r_c are the clusters tidal and core radii, respectively. Van den Bergh (1994) has shown that both true globular clusters and old populous red clusters in the LMC appear to follow Eqn.(1). It is not yet understood why the luminosity (mass) and central concentration of clusters should be so well correlated.

5. Capture of Globular Clusters

Lin & Richer (1992) have argued that the globular clusters Ruprecht 106, and perhaps also Palomar 12, (which appear to be a few Gyr younger than typical halo clusters) were tidally captured from the Magellanic Clouds.

Some data on these two clusters are summarized in Table 1. Pal 12 ([Fe/H] = -1.14) falls outside the range -2.17 [Fe/H] - 1.37 observed for true globular clusters (Suntzeff 1992) in the LMC. With an age > 10 Gyr, Pal 12 is also too old (and too metal-poor) to be related to the old red populous cluster population in the Large Cloud. However, Pal 12 might have been stripped from the SMC, in which clusters with ages of 4 - 12 Gyr are observed to have [Fe/H] ≈ -1.3 (Da Costa 1991).

TABLE 1. Properties of Palomar 12 and Ruprecht 106

Cluster	r_c(pc)	[Fe/H]	ΔT(Gyr)
Pal 12	6.2	-1.14	3
Rup 106	5.8	-1.9	4.5

The relatively large core radii (Rodgers & Roberts 1994) of Pal 12 (r_c = 6.2 pc) and Rup 106 (r_c = 5.8 pc) are similar to that of NGC 2257 (r_c = 6.1 pc), which is located 8°.5 from the LMC. The observation that Rup 106 and Pal 12 have radii similar to those of clusters in the inner halo of the LMC [but which are larger than those in the core of the Large Cloud!] is compatible with the stripping hypothesis of Lin & Richer (1992).

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DISCUSSION

K. Freeman: Concerning the comparison of luminosity functions for open and globular clusters: from the work of Weinberg and others, we know that young clusters of lower concentration or flatter mass function will evaporate. So perhaps one should include only clusters with ages greater than say 5×10^7yr in this comparison.

van den Bergh: I agree that both evaporation and interactions with GMCs will lead to the destruction of many low-mass clusters. However, the fact that globulars in very different environments (bulge, disk, halo, M31, giant ellipticals) have similar luminosity functions suggests to me that the faint end of the globular cluster luminosity function is not entirely determined by cluster destruction.

A. Renzini: I'd like to ask a very naive question – In the first picture you have shown the metal rich clusters are very concentrated towards the galactic center, rather than flattening about the Disc, with the vast majority of them physically lying within the Bulge – So, why are they called "Disc" rather than "Bulge" clusters?

van den Bergh: You are quite right! Another example of such poor nomenclature is that Supernovae at Type II belong to Population I.