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The Connection between Globular Cluster Systems and the Host Galaxies

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\vspace{1em}

\begin{abstract}
A large number of early type galaxies are now known to possess blue and red subpopulations of globular clusters. We have compiled a database of 28 such galaxies exhibiting bimodal globular cluster colour distributions. After converting to a common V–I colour system, we investigate correlations between the mean colour of the blue and red subpopulations with galaxy velocity dispersion. We support previous claims that the mean colour of the blue globular clusters are unrelated to their host galaxy. They must have formed rather independently of the galaxy potential they now inhabit. The mean blue colour is similar to that for halo globular clusters in our Galaxy and M31. The red globular clusters, on the other hand, reveal a strong correlation with galaxy velocity dispersion. Furthermore, in well-studied galaxies the red subpopulation has similar, and possibly identical, colours to the galaxy halo stars. Our results indicate an intimate link between the red globular clusters and the host galaxy; they share a common formation history. A natural explanation for these trends would be the formation of the red globular clusters during galaxy collapse.

\textbf{Key words:} galaxies: interactions - galaxies: elliptical - globular clusters: general - galaxies: evolution
\end{abstract}

\section{Background Motivation}

Globular clusters are relatively homogeneous entities containing stars of a single age and metallicity. Although we do not fully understand the relative efficiency of forming globular cluster (GC) stars over galactic field stars, there is good evidence that when a starburst occurs in a galaxy, GCs will also form (e.g. Ho 1997). Thus GCs can provide a unique probe of the star formation and chemical enrichment history of galaxies. To fully exploit this ‘probe’ one needs to have an idea for how GCs form in galaxies. Current scenarios include mergers (Schweizer 1987; Ashman \& Zepf 1992), two phase \textit{in situ} (Forbes, Brodie \& Grillmair 1997) and tidal stripping/accretion (Forte, Martinez \& Muzzio 1982; Cote, Marzke \& West 1998).

A direct comparison of GC and host galaxy colours was first attempted in the late 1970s and early 1980s (e.g. Hanes 1977; Forte, Strom \& Strom 1981). A difference in colour was observed, in the sense that GCs were \textasciitilde 0.5 dex more metal–poor than galaxy stars. This lead Forte \textit{et al.} (1981) to conclude that “...the chemical enrichment history of the globular cluster system and of the spheroidal component must have differed, and that the globular clusters are likely to form a component dynamically as well as chemically distinct from the spheroid.”

However another line of argument has developed indicating that there is a link between GCs and their host galaxy. This involves the correlation between the mean metallicity of the GC system and galaxy luminosity. Such a trend was first suggested by van den Bergh (1975) and shown by Brodie \& Huchra (1991), but for only 10 galaxies. It was later disputed by Ashman \& Bird (1993) claiming that there was no correlation, and by Perelmuter (1995) claiming that the relation only existed for spirals. In 1996, Forbes \textit{et al.} showed a strong trend over 10 magnitudes for 35 early type galaxies. Subsequent larger samples have confirmed a correlation (e.g. Durrell \textit{et al.} 1996). Although the scatter is large, a linear fit has a slope very similar to that for the
galaxy stellar metallicity versus galaxy luminosity relation, i.e. \( Z \propto L^{0.4} \) (see Brodie & Huchra 1991).

The galaxy relations, like the \( \text{Mg}_2 - \sigma \) and the colour – magnitude relations, are generally believed to be correlations of metallicity and mass (Kodama & Arimoto 1997; Forbes, Ponman & Brown 1998). Thus by analogy, the mean metallicity of the GC system ‘knows about’ the mass of the galaxy in which it resides; the chemical enrichment of GCs is directly linked to the galaxy formation process.

It wasn’t until the 1990s that we could easily understand the apparent metallicity difference between the GC system and the host galaxy (as noted by Forte et al. 1981) – it is due to the presence of two distinct GC subpopulations (e.g. Lee & Geisler 1993). The metallicity difference being due to the relative mix of metal-rich and metal-poor GC subpopulations. It appears that the metal-rich GCs have a mean metallicity that is similar to the host galaxy stars whereas this is often the case for elliptical galaxy GCs. However we first need to confirm that it is applicable for the GC systems of early type galaxies.

Revisiting the metallicity – luminosity relation, Forbes et al. (1997) showed that for 11 GC systems the metallicity of the metal-rich population correlated with galaxy luminosity, but the metal-poor one did not (see also Burgarella, Kissler-Patig & Buat 2000). Forbes et al. (1997) concluded that only the metal-rich GCs were closely linked to the formation process of the galaxy.

However one caveat about the interpretation of the GC metallicity – galaxy luminosity relation is that metallicities are usually based on colours that have been converted into [Fe/H] assuming a Galactic relation. This has two limitations:

i) The Galactic relation is strictly only valid for very old GCs. The limited current evidence suggests that GCs around ellipticals are indeed very old (Kissler-Patig et al. 1998; Cohen, Blakeslee & Rhyzov 1998; Puzia et al. 1999), but this may not always be the case.

ii) Few Galactic GCs have solar or supersolar metallicities, whereas this is often the case for elliptical galaxy GCs. Recently a conversion from V–I to supersolar metallicities has been derived by Kissler-Patig et al. (1998), but it is still somewhat uncertain for other colour systems.

So although it seems fairly probable that the metal-rich GCs formed from gas that has been processed within the potential well of the galaxy, previously arguments relied on the assumption that the Galactic relation is applicable. In this paper, we use direct measurements of GC colours and compare these to galaxy internal velocity dispersions for a sample of 28 galaxies. Our approach alleviates some of the problems associated with metallicity – luminosity relations mentioned above. In addition, we avoid the distance dependence present in the metallicity – luminosity relation. We also examine the GC and galaxy halo colours in detail for a few individual galaxies. We find that the mean colour of the red GCs correlates with galaxy velocity dispersion. Furthermore, in well-studied galaxies the mean colour of the red GCs is almost identical to the galaxy halo (bulge) stars. We briefly discuss the implications of our findings for GC formation scenarios.

## 2 Conversion to a Single Colour System

The bulk of high quality GC colours, available in the literature, come from Hubble Space Telescope studies, and most of these use the F555W (V) and F814W (I) filters. Although this choice of filters does not provide as much metallicity ‘leverage’ as say B–I or C–T1 (on the Washington system), a large number of early type galaxies are now known to possess GC systems with bimodal V–I colour distributions. Several more are known from observations in other colour systems. Before compiling a homogeneous dataset of GC colours we need to convert the bimodality seen using other colour systems into V–I. We will use a V–I vs colour relation based on Galactic GCs, however we first need to confirm that it is applicable for the GC systems of early type galaxies.

In Fig. 1 we show the extinction corrected (V–I)\(_o\) versus \((C–T1)_o\) and \((B–I)_o\) colour for Galactic GCs with low reddenings (i.e. E(B–V) < 0.1) taken from Reed, Hesser & Shaw (1988) and Harris & Cantiello (1977). The best bisection fits are shown by a solid lines. We have also made a fit to transform B–R to V–I (not shown in Fig. 1). The fits are the following:

\[
\begin{align*}
(V–I)_o &= 0.49(C–T1)_o + 0.32 \\
(V–I)_o &= 0.51(B–I)_o + 0.11 \\
(V–I)_o &= 0.68(B–R)_o + 0.15
\end{align*}
\]

The typical rms about the fits is ± 0.03 mag. Thus one could expect to estimate V–I for a Galactic type GC with an accuracy of ~ 0.03 mag. from a different colour.

Fig. 1 also shows the mean blue and red colours for the GCs in the well-studied galaxies NGC 1399, NGC 4472 (M49) and NGC 4486 (M87). Here we have plotted the \((C–T1)_o\) measurements for NGC 1399 (Ostrov, Forte & Geisler 1998), NGC 4472 (Geisler, Lee & Kim 1996), and NGC 4486 (Lee & Geisler 1993) and the \((B–I)_o\) values for NGC 1399 (Forbes et al. 1998). The corresponding \((V–I)_o\) values are from NGC 1399 (Kissler-Patig et al. 1997), NGC 4472 (Puzia et al. 1999) and NGC 4486 (Kundu et al. 1999). The GC systems of these galaxies are consistent with the Galactic relation, including an extrapolation to redder (more metal-rich) colours. Thus we feel confident in our transformation from C–T1 and B–I into V–I. We do not have any independent confirmation of the B–R transformation but have no reason to doubt that it too is applicable to GCs in ellipticals.

In Table 1 we list the mean \((V–I)_o\) colours for the GC subpopulations in 28 galaxies. Of these, only four have been transformed from other colour systems (as noted in Table 1). The estimated photometric errors for the mean colours are typically ± 0.05 mag. (this includes the uncertainty of transformation from one colour system to V–I). The confidence of bimodality is given by ‘Yes’ for definite and ‘Likely’ for probable. In most cases the statistical significance of the bimodality can be found in the original reference.

## 3 Results and Discussion

### 3.1 Trends with Velocity Dispersion

In Fig. 2 we show the mean \((V–I)_o\) colour of the GC subpopulations versus the galaxy velocity dispersion for all of
Figure 1. $(V-I)_o$ vs $(C-T)_o$ and $(B-I)_o$ colour relation for Galactic globular clusters. Open squares represent Galactic globular clusters with low reddening, and filled circles the blue and red globular cluster populations of NGC 1399, 4472 and NGC 4486. The solid line is a fit to the Galactic globular clusters only.

The galaxies listed in Table 1. The velocity dispersion data come from Prugniel & Simien (1996).

The blue GCs show no correlation with galaxy velocity dispersion. Indeed they reveal a fairly constant colour of $(V-I)_o = 0.954 \pm 0.008$. This is very similar to the overall mean colours of the Milky Way (0.94 ± 0.01) and M31 (0.96 ± 0.01) GC systems (see Barmby et al. 2000). If we exclude the disk/bulge populations of GCs in these spirals, then the halo GCs in both galaxies have a mean $(V-I)_o \sim 0.92$ (Barmby et al. 2000). Thus the blue GCs in spirals and early type galaxies have a very similar age and metallicity, but there are hints that those in spirals may be slightly younger and/or more metal–poor.

The red GCs, on the other hand, reveal a strong correlation (at 3σ significance) of mean colour with galaxy velocity dispersion. The best fit line for the red GCs $(V-I = 0.23 \log \sigma + 0.61)$ is shown in Fig. 2. Galaxy velocity dispersion is a tracer of galaxy mass. Thus the colour (and presumably metallicity) of the red GCs is directly linked to the depth of the galaxy’s potential well.

We note that if we had converted the C–T1 measurements of Secker et al. (1995) for NGC 3311 then the colours of the blue $(V-I = 1.15)$ and red $(V-I = 1.28)$ GCs would deviate strongly from the trends seen in Fig. 2. However we used the more recent results of Brodie, Larsen & Kissler–Patig (2000) which indicate normal GC colours for NGC 3311. We suspect zero point errors in the Secker et al. (1995) analysis. This may also affect the C–T1 colours (Zepf et al. 1995) for the NGC 3923 GC system which was observed on the same run (we have assigned it a larger error). Indeed NGC 3923 is one of the more deviant points in Fig. 2.
3.2 Trends with Galaxy Halo Colour

Having shown that the red GC subpopulation has a direct connection with the host galaxy, while the blue subpopulation is unconnected we now explore the trend between mean GC colour and galaxy halo colour.

In order to best compare GC and galaxy colours, the colours should come from the same observations, and sample a similar galactocentric annulus around any given galaxy as radial gradients may exist in the galaxy and GC subpopulations (e.g. Ostrov et al. 1998; Forte et al. 2000). We have also decided to restrict our analysis to the wide–area studies conducted using C–T1 (which has the best metallicity sensitivity of GC studies). This excludes HST studies which typically probe only the galaxy inner regions in V–I. With these criteria we found four galaxies (the Secker et al. (1995) C–T1 data on NGC 3311 has been excluded for reasons mentioned above). The four are NGC 1399 (Ostrov et al. 1998), NGC 1427 (Forte et al. 2000), NGC 3923 (Zepf et al. 1995), NGC 4472 (Geisler et al. 1996; Lee & Kim 2000) and NGC 4486 (Geisler et al. 2000). We note that the zero points and hence colours of NGC 3923 may be in error (as discussed above) but as the galaxy and GCs colours come from the same observation this will not effect the relative colour difference. The two papers referenced for NGC 4472 use the same data collected in 1993. Where possible, colours have been taken from similar galactocentric radii. In the case of NGC 1399, Ostrov et al. (1998) quote galaxy and GC colours in three radial bins for the red subpopulation and two bins for the blue ones.

The mean GC colours versus galaxy halo colour is shown in Fig. 3. The mean blue GC colours do not reveal a strong trend with halo colour, and in particular lie well away from a one-to-one relation. However the red GCs do lie close...
Figure 3. Mean C–T1 colour of the globular clusters and galaxy halo. Globular cluster and galaxy colours are taken from the same source, and matched in galactocentric radius where possible. For NGC 1399 colours at different galactocentric radii are shown. See text for details. The dashed line shows a one-to-one relation. Within the errors, red globular clusters have identical C–T1 colours to the host galaxy halo.

So not only do red GCs have a metallicity that is linked to the depth of the galaxy’s potential well (Fig. 2), for at least some galaxies they also have the same metallicity as the galaxy halo stars. This suggests a very well coordinated star formation and chemical enrichment history.

For the NGC 1399 red GCs, the agreement is not only restricted to the mean colours discussed above, but also in the sense that they share the same colour gradient as the underlying galaxy halo (see table 5 in Ostrov et al. 1998). If the galaxy halo was in fact related to the overall GC system, then halo colour gradients would reflect the varying ratio of the blue to red GCs with galactocentric radius. However if this were the case, we would expect the halo colour gradient to get significantly bluer with increasing radius (as the blue GCs dominate). For NGC 1399 (Ostrov et al. 1998) this is not the case indicating that the halo colours do not reflect the blue GCs, but rather the red ones.

Finally, we note that in recent ground-breaking work, Harris et al. (1999) used HST to resolve the stars in the halo of NGC 5128. They showed that the red halo stars and the metal–rich GCs have the same metallicity, and concluded that they formed in the same star formation event.

3.3 How did the Red Globular Clusters Form?

The simplest explanation for the fact that the red GCs and the galaxy stars may have similar colours, and that red GCs colours correlate with galaxy velocity dispersion, is that they formed at the same time from the same chemically enriched gas. This would naturally favour the two phase collapse sce-
nario (Forbes et al. 1997). In this scenario the red GCs form almost contemporaneously with the galaxy field stars, and hence share their properties. The trends described here are a natural consequence of this idea.

Are these trends expected in the merger picture (Ashman & Zepf 1992)? After a gaseous merger the galaxy will consist of at least two stellar and two GC populations (the first associated with the progenitor galaxies and the other created in the merger). The relative ratios of these two components depend on how much gas is available to create the new stars and GCs. The gas fraction would be high at early epochs. To explain Fig. 2 one could argue that the more metal-rich (redder) GCs were created in the merger. The relative ratios of these two components would then argue that the halo is dominated by new stars identical colours of the galaxy halo and red GCs (Fig. 3), consistent with the progenitors were largely formed at the same time, from the same gas, as the new (red) GCs. The gas fraction would be high at early epochs. To explain Fig. 2 one could argue that the more metal–poor (bluer) GCs form in situ (Ashman et al. 1998). In this scenario the red GCs form in situ, but the blue ones are accreted, along with starlight, from stripped dwarf galaxies. This accumulation of metal–poor material into the halo of the primary galaxy would tend to make the halo light bluer than the red GCs – in contradiction to what is seen in Fig. 3.

In the accretion model of Cote et al. (1998), the red GCs form in situ but the blue ones are accreted, along with starlight, from stripped dwarf galaxies. This accumulation of metal–poor material into the halo of the primary galaxy would tend to make the halo light bluer than the red GCs – in contradiction to what is seen in Fig. 3.

4 CONCLUDING REMARKS

Here we have presented evidence that the mean colour of the blue GCs in early type galaxies are unrelated to their host galaxy, supporting the work of Forbes et al. (1997) and Burgarella et al. (2000). In terms of a collision scenario, where the blue GCs form in a proto–galactic dark matter halos, they do not appear to have ‘memory’ of the collision phase suggesting they formed pre–collapse or possibly quite independently of the eventual host galaxy (Burgarella et al. 2000). We note however, that this is probably not true for the Milky Way halo globular clusters (the ‘blue’ subpopulation). These metal–poor globular clusters do show evidence that the majority formed within our Galactic halo (van den Bergh 1996).

The red GCs, on the other hand, do ‘know’ about the galaxy they occupy in terms of its potential well and halo colour. This suggests that the red GCs and the host galaxy share a common formation event. This naturally favours the two phase collision picture, in which the red GCs and the halo stars are formed together (Forbes et al. 1997). The merger picture (Ashman & Zepf 1992) is only compatible if the merger took place at early epochs involving gaseous progenitors.

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| Galaxy Name | Blue Peak  | Red Peak  | Bimodal | Ref. |
|-------------|------------|-----------|---------|-----|
| NGC 584     | 0.98±0.05  | 1.18±0.05 | Likely  | K99 |
| NGC 1023    | 0.92±0.05  | 1.17±0.05 | Yes     | LB00|
| NGC 1380    | 0.86±0.10  | 1.10±0.10 | Yes     | KK97a|
| NGC 1399    | 0.99±0.05  | 1.18±0.05 | Yes     | KR97 |
| NGC 1404    | 0.93±0.10  | 1.18±0.10 | Yes     | F98b |
| NGC 1427    | 0.98±0.05  | 1.16±0.05 | Yes     | F00c |
| NGC 1439    | 0.97±0.05  | 1.16±0.05 | Likely  | K99 |
| NGC 2768    | 0.92±0.05  | 1.12±0.05 | Yes     | K99 |
| NGC 3115    | 0.96±0.05  | 1.17±0.05 | Yes     | KW98 |
| NGC 3311    | 0.91±0.05  | 1.09±0.05 | Yes     | B00 |
| NGC 3377    | 0.96±0.05  | 1.13±0.05 | Likely  | K99 |
| NGC 3379    | 0.94±0.05  | 1.16±0.05 | Likely  | K99 |
| NGC 3923    | 1.04±0.10  | 1.24±0.10 | Yes     | Z95c |
| NGC 4278    | 0.93±0.05  | 1.13±0.05 | Likely  | K99 |
| NGC 4406    | 0.98±0.05  | 1.17±0.05 | Likely  | K99 |
| NGC 4472    | 1.00±0.05  | 1.23±0.05 | Yes     | P99 |
| NGC 4473    | 0.93±0.05  | 1.15±0.05 | Yes     | K99 |
| NGC 4486    | 0.95±0.05  | 1.20±0.05 | Yes     | KW99 |
| NGC 4494    | 0.95±0.05  | 1.15±0.05 | Yes     | F96 |
| NGC 4526    | 0.85±0.05  | 1.15±0.05 | Yes     | G99 |
| NGC 4552    | 0.96±0.05  | 1.18±0.05 | Likely  | K99 |
| NGC 4621    | 0.98±0.05  | 1.16±0.05 | Yes     | K99 |
| NGC 4649    | 0.95±0.05  | 1.20±0.05 | Yes     | K99 |
| NGC 4660    | 0.93±0.05  | 1.08±0.05 | Likely  | K99 |
| NGC 5846    | 0.96±0.05  | 1.17±0.05 | Yes     | F97 |
| NGC 5982    | 0.99±0.05  | 1.18±0.05 | Likely  | K99 |
| IC 1459     | 1.00±0.05  | 1.25±0.05 | Yes     | F96 |
| IC 4051     | 1.00±0.05  | 1.17±0.05 | Likely  | WH00 |

NOTES: a = transformed from B−R; b = transformed from B−I; c = transformed from C−T1. B00 = Brodie et al. (2000); F96 = Forbes et al. (1996); F97 = Forbes et al. (1997); F98 = Forbes et al. (1998); F00 = Forte et al. (2000); G99 = Gebhardt & Kissler-Patig (1999) KK97 = Kissler-Patig et al. (1997b); KR97 = Kissler-Patig et al. (1997a); KW98 = Kundu & Whitmore (1998); K99 = Kundu (1999); kW99 = Kundu et al. (1999); LB00 = Larson & Brodie (2000); P99 = Puzia et al. (1999); Z95 = Zepf et al. (1995); S95 = Secker et al. (1995); WH00 = Woodworth & Harris (2000).