Near-Field Cosmology with Dwarf Elliptical Galaxies
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Globular clusters and nuclei in dwarf ellipticals

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Abstract. Globular clusters (GCs) and nuclei in dEs are important probes for for studying cosmology and galaxy evolution. GCs and nuclei are usually formed in the high pressures of starbursts, therefore resolved stellar color-magnitude diagrams and integrated colors, magnitudes, or spectra yield ages and metallicities which are snapshots of the conditions during the most violent and important star forming episodes of the galaxies. Most are older, more metal-poor, and more enriched in α-elements than the underlying dE field stars. About 25% have formed within the last $\sim$6 Gyr from enriched gas. Many nuclei have the properties of brights GCs but some can be distinguished by large sizes and composite stellar populations. The relatively large numbers of GCs in dEs shows that they are an important source of GCs to galaxies that accrete them.

Keywords. galaxies: dwarf, galaxies: star clusters, galaxies: nuclei

1. Introduction

The aim of near-field cosmology is to use local objects which can be studied in great detail to try to unravel the earliest periods of galaxy formation and evolution. What is discovered should be consistent with the results from high redshift galaxy studies and the values of the cosmological parameters. Globular clusters (GCs) are very useful tools for this endeavor: they are normally made of simple (single-age) stellar populations so they can be dated relatively easily; they are compact and luminous so they can be detected at large distances; and they are fairly numerous in dwarf elliptical (dE) galaxies. They have also been found to be among the oldest stellar systems known. Therefore, they provide an important view back to the earliest periods of star and galaxy formation and they have played a fundamental role in determining the formation history of the galaxy (e.g. Searle & Zinn 1978).

Nuclei are identified as distinct compact structures in the centers of galaxies. Nuclei are found in the centers of disk galaxies as well as in over half of bright dE galaxies in galaxy clusters. Nucleated dwarfs are the dominant galaxy population by number in rich galaxy clusters but their fraction decreases in lower density environments (Ferguson & Sandage 1989). A detailed comparison of GCs and nuclei may help determine how nuclei can form. Also, a comparison of the nuclei in spirals and dEs can help determine if some nucleated dEs are the harassed remnants of spiral galaxies.

This paper will review the basic properties of GCs and nuclei in nearby dE galaxies. We use the term dE to refer both to brighter systems like NGC 205 and the low surface-brightness systems like Fornax that are sometimes referred to as dwarf spheroidals (dSph). Detailed information about the stars within GCs in the Local Group will help us interpret the larger samples of GCs in more distant galaxies where only integrated properties can be measured. Finally, some inferences will be drawn about the formation of GCs in the context of our current understanding of the conditions in the early universe.

Galaxy	M_V	N_{GC}	Nuc	$\langle V-I\rangle_{GC}$	$[Fe/H]_{GC}$	$[Fe/H]_{FS}$	δt_{GC}
Fornax	−13.1	5	Yes?	0.83	−1.8	−0.9	3 Gyr
Sagittarius	−13.5?	6	Yes?	0.89	−1.6	−0.5	6 Gyr
NGC 147	−15.2	2	No	0.75	−2.0	−0.9	$<$ 2 Gyr
NGC 185	−15.5	5	No	0.86	−1.7	−1.2	$<$ 2 Gyr
NGC 205	−16.6	7	Yes	0.95	−1.4	−0.8	10 Gyr

Table 1. Globular cluster systems in Local Group dE galaxies. Data are taken from Lotz *et al.* (2004), Forbes *et al.* (2004), and references therein. δt_{GC} is the age spread of the GCs.

2. The Local Group

Of the approximately 20 dE/dSph galaxies known in the Local Group only 5 have massive star clusters. The properties of these star cluster systems are given Table 1. Some have proposed that between 4 and 6 GCs may also be associated with the newly discovered Canis Major dwarf (Martin *et al.* 2004; Forbes *et al.* 2004). However, Martínez-Delgado (2005) reports that new proper motions exclude these clusters from being associated with this galaxy. Therefore, we will not consider the Canis Majoris system.

Three of the five galaxies in Table 1 are possibly nucleated. NGC 205 has a clear nucleus but this nucleus is less than 1 Gyr old. Both Fornax and Sagittarius have globular clusters near the peaks in their background light distributions and so these are considered candidate nuclei (Da Costa & Armandroff 1995; Strader *et al.* 2003).

A defining characteristic of GCs is their small size. Half-light radii (R_h) are typically 3–5 pc but they can be as large as 30 pc (Figure 1). The sizes of GCs associated with the Sagittarius dE are the same as typical Galactic GCs. There may be an upper envelop to R_h at a given M_V for typical GCs that is indicated by the solid line in (Figure 1. The few objects that lie above this line are unusually large for their luminosities. M54 is the central GC in the Sagittarius dwarf and it may have a spread in internal abundances (Da Costa & Armandroff 1995). Omega Cen also has multiple stellar populations and it has been speculated that it is the former nucleus of a disrupted dwarf (Hilker & Richtler 2000). The one unambiguous dE nucleus in the Local Group belongs to NGC 205 (Butler & Martínez-Delgado 2005). It also falls on or just above the line in Figure 1. Therefore, dE nuclei have compact sizes similar to those of GCs but they may be distinguishable by having sizes that are relatively large for their luminosities.

The bane of stellar population studies is breaking the degeneracy between age and metallicity that is always present in the observations. Nearby GCs that can be resolved into stars are the among best environments for breaking this degeneracy and do consistency checks of different techniques. We will use the Fornax GCs as an example of the different methods and their uncertainties.

Figure 2 shows the color-magnitude diagrams (CMDs) of two GCs in the Fornax dwarf from images taken with *HST* (Buonanno *et al.* 1998). The narrow giant branch and single, well-defined main sequence turnoff are indicative of a simple (single age and metallicity) stellar population. Isochrones from stellar evolutionary models are fit to the CMDs to determine the ages, metallicities, reddenings, and distances. This analysis shows that they have low metallicities, ranging between [Fe/H] $= -1.8$ and [Fe/H] $= -2.2$, and age differences of less than 1 Gyr. These clusters are coeval with the Galactic GC M68 and perhaps 1–2 Gyr younger than the prototypical old GC M92. Similar analysis of the centrally-located cluster H4 shows that is has the same metallicity as the other Fornax clusters but that it is about 3 Gyr younger (Buonanno *et al.* 1999).

Ages and metallicities derived from spectroscopy should be consistent with the results from resolved stellar photometry, but this is not always the case. The analysis of low

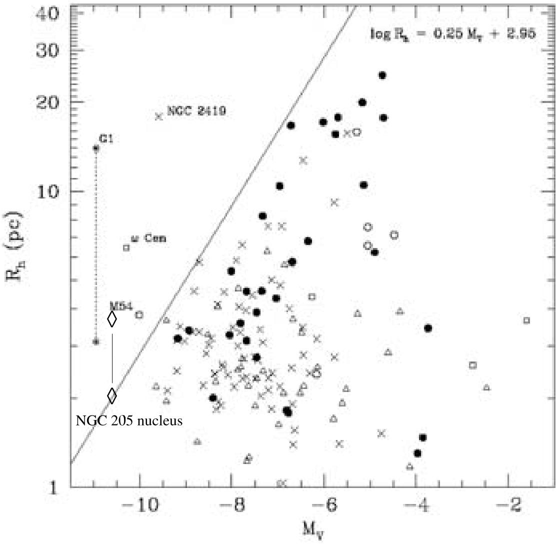

Figure 1. Half-light radii versus absolute magnitude for Galactic and Sagittarius globular clusters (from (Mackey & van den Bergh 2005). The symbols represent the following: open triangles — bulge/disk clusters; crosses — old halo clusters; filled circles — young halo clusters; open circles — Sagittarius clusters; asterisks — M31 globular G1; diamonds — NGC 205 nucleus; and squares — unclassified. The solid line approximates the upper envelope of the R_h vs.M_V trend for typical GCs. Objects that lie above this line are potential dE nuclei.

resolution spectra involves the measurement of "indices" of the most important lines of H, Fe, Mg, and Ca (e.g. Worthey 1994). Strader *et al.* (2003) has measured metallicities of the GCs in Fornax using Lick indices that agree with the photometric results for the outer clusters. However, cluster H4 is found to have a higher metallicity of [Fe/H] = −1.5. The ages are found to be old but cluster H5 may be 2–3 Gyr younger than the others.

Another property of cluster CMDs that is related to age and metallicity is the horizontal branch (HB) morphology. In general metal-poor GCs have blue horizontal branches (high HB index) while metal-rich GCs have red horizontal branches (low HB index). However, some clusters like H1 in Fornax (Figure 2) are metal-poor but have red horizontal branches. This is the 2^{nd} parameter effect. Age is a likely 2^{nd} parameter but this cannot be the case for Fornax H1 if the photometrically-derived ages and metallicities are correct. Figure 3a shows metallicity versus HB index for the Fornax and the Galactic GCs. If age is the 2^{nd} parameter then the models predict that H1 should be 1–2 Gyr younger than the photometry suggests. Buonanno *et al.* (1998) suggest that a low central stellar density might be the second parameter in this case. H4 is ambiguous, if young and metal-poor then it is consistent with age being the 2^{nd} parameter, but if it is older and metal-rich, as suggested by spectroscopy, then its HB is explained by its metallicity and age.

The GCs in Sagittarius also have a range of ages and metallicities. Four of the six clusters have ages greater than 10 Gyr and [Fe/H] ~ -1.8. However, Pal 12 and Terzan 7 have ages of 6–7 Gyr and [Fe/H] ~ -0.9. Their HB morphologies are consistent with age being the 2^{nd} parameter (Figure 3b). Studies of the field stars in Sagittarius show that they are more metal-rich and younger on average than the GCs (see Forbes *et al.* 2004). Table 1 shows that this is a general characteristic of dEs. Interestingly, the stars and GCs in Sagittarius are consistent with the same age-metallicity relation (Layden & Sarajedini 2000; Forbes *et al.* 2004). Also, Layden & Sarajedini (2000) find evidence for

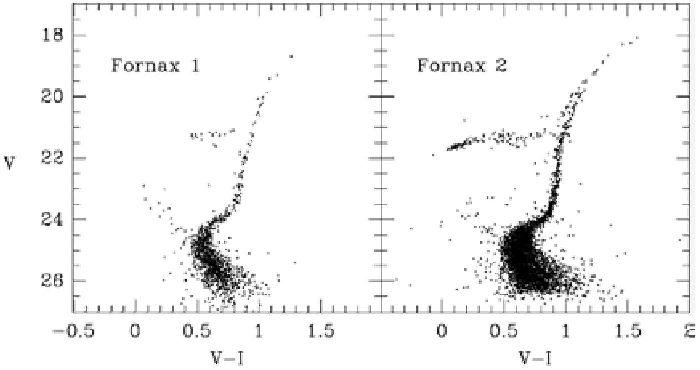

Figure 2. Color-magnitude diagrams of two GCs in the Fornax dwarf (Buonanno *et al.* 1998).

enhanced star formation at look-back times of 5 and 11 Gyr, consistent with the GCs forming during the most vigorous star formation episodes. The picture in Fornax is very similar (Pont *et al.* 2004). Therefore, in dEs star clusters can help us trace the galaxies' overall star formation and chemical enrichment histories.

The abundance ratios the α-elements (O, Mg, Ca, Ne, Si, Su, Ar, Ti) with respect to iron provide the next level of detail about a system's chemistry and star formation history (see the related contributions in these proceedings). The [α/Fe] ratio is a useful diagnostic of star formation history because Fe is produced mainly in Type Ia supernovae while the α elements are produced primarily in Type II supernovae. Therefore, high [α/Fe] is indicative of a time during or just after a vigorous starburst while a lower, solar, value of [α/Fe] is the result of a long period of quiescent or continuous star formation.

Most of the current information on [α/Fe] in dEs comes from studies of Sagittarius. The suggested nucleus, M54, has [α/Fe] ~ 0.2 (Brown *et al.* 1999). This is larger than the solar ratio and somewhat below the values of $\sim$0.3 seen in Galactic and M31 GCs (Carney 1996, Beasley *et al.* 2005). The young, metal-rich clusters Pal 12 and Terzan 7 have [α/Fe] consistent with the solar value (Brown *et al.* 1997; Tautvaišienė *et al.* 2004) and the abundance ratios in Pal 12 are similar to the ratios of Sagittarius field stars (Cohen 2004). This supports the earlier picture that the GCs and field stars in Sagittarius share a common enrichment history and that Pal 12 and Terzan 7 formed from gas enriched by several Gyr of star formation. It also shows that the timescale for Type Ia enrichment between 3 and 6 Gyr (see Carney 1996).

Measurements of [α/Fe] in Fornax are scarce at the moment. Strader *et al.* (2003) speculate that the differences between photometric and spectroscopic metallicities in H4 could be explained if it has a lower [α/Fe] than the other clusters.

3. dE Globular Cluster Systems

Larger samples of dEs with GCs and nuclei are needed in order to study the statistical properties of dE globular cluster systems (GCSs) such as the luminosity function (GCLF), the spatial distribution of GCs, the specific globular cluster frequency (S_N), and dependencies on galaxy luminosity and environment. The largest sample of dE GCSs the WFPC2 dE Snapshot Survey (Lotz *et al.* 2004) which has observed 69 dEs in the Virgo and Fornax Clusters and the Leo Group. The ACS surveys of the Virgo and Fornax Clusters (Côté, these proceedings) will take this work to the next level by adding distances to the individual galaxies.

The criteria for selecting GC candidates in these surveys are size (FHWM < 20 pc at Virgo for the WFPC2 sample), integrated color similar to that of Galactic GCs, and number density greater than that of a field sample. Both the mean $V-I$ color and the color dispersion of dE GCs increases with galaxy absolute magnitude (Strader *et al.* (2004); Lotz *et al.* 2004; see Figure 4). The colors and color trend for GCs in dEs matches those of GCs in the *blue* GC populations of giant Es and S0s. The blue GSs in E/S0s have properties similar to Galactic GSs, so this is consistent with GCs in Local Group dEs being similar to Galactic halo GCs. The red peak in the bimodal E/S0 GC color distributions is thought to be due to a second period of GC formation, perhaps during mergers (Ashman & Zepf 1992).

The mean colors of the field stars in the WFPC2 dE sample are 0.1 to 0.2 mag redder than the mean GC colors. In nucleated dEs there is a trend that the field-star colors become redder with galaxy M_B. There is a shallower trend for the non-nucleated dwarfs.

At a given absolute magnitude there is no color difference between nuclei and GCs. However, brighter galaxies have brighter and redder nuclei (Graham & Guzmán 2003; see Figure 5). From WFPC2 the nuclei are $\sim$0.05 mag redder in $V-I$ than the GCs and between 0.0 and 0.1 mag bluer than the underlying stars. Other studies have tended to find no color differences between the nuclei and their galaxies (Caldwell & Bothun 1987).

Integrated $V-I$ colors suffer from age/metallicity degeneracy so we must make some assumptions about one property before deriving the other. The mean GC colors are the same as the integrated colors of old, metal-poor GCs in Sagittarius and Fornax (Table 1). Also, spectroscopy of the field-star light gives a mean age of $\sim$6 Gyr and [Fe/H] ~ -0.3 (Geha *et al.* 2003). We know that in the Local Group most GCs in dEs are older and more metal-poor than the mean field-star population. Finally, the GCLF is consistent with the GCLF of an old, metal-poor population (Miller 2003). Therefore, a consistent and reasonable conclusion is that most GCs in the WFPC2 sample are older than 10 Gyr.

For an old stellar population one can convert $V-I$ to metallicity using $[\mathrm{Fe/H}] = -4.50 + 3.27(V-I)$ (Kissler-Patig *et al.* 1998). Therefore, the observed trend in GC color with galaxy M_B gives $Z_{GCs} \propto L_B^{0.2}$. This is shallower than $Z_{FS} \propto L_B^{0.4}$ found for

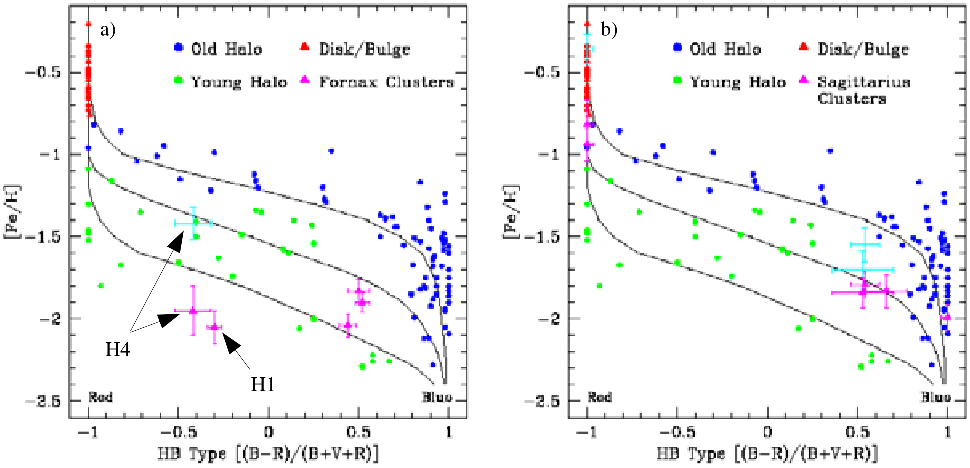

Figure 3. Horizontal-branch index versus metallicity for the Fornax and Sagittarius dwarfs in comparison with different populations of Galactic GCs (from Mackey & Gilmore 2004). Cyan (light) triangles with errors bars represent higher-metallicity measurements for a given cluster. The curves are isochrones from the models of Rey *et al.* (2001). The middle and lower isochrones are 1.1 Gyr and 2.2 Gyr younger than the top isochrone.

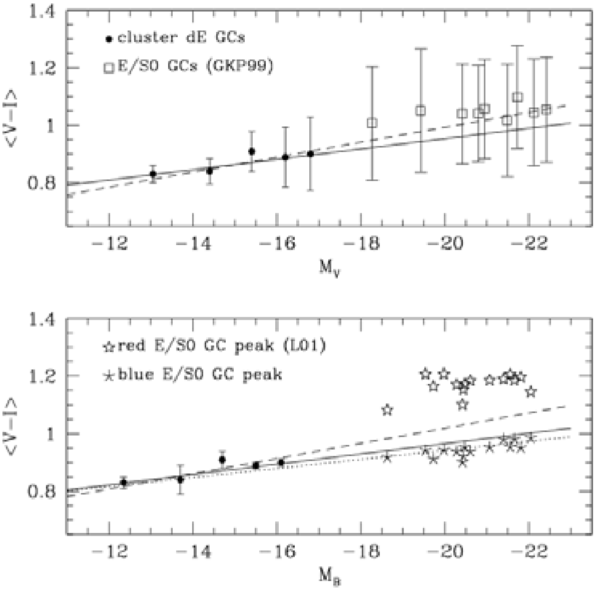

Figure 4. GC color versus galaxy magnitude (from Lotz *et al.* 2004). *Top*: Mean $V - I$ vs. host galaxy M_V. The error bars give the dispersion in the color. *Bottom*: Mean $V - I$ for the dEs and red and blue peak colors of 16 E/S0s versus host galaxy M_B. Error bars on the dE points are now the uncertainties in the mean. The solid line is fit to $\langle V - I\rangle - M_V$ for the WFPC2 sample only while the dashed line includes dEs from the literature. The dotted line is the fit to the blue E/S0 points from Larsen *et al.* (2001).

nearby field star populations (Dekel & Silk 1986) but consistent with the trends in field-star colors seen in the WFPC2 data. The shallower slopes can be explained if adiabatic winds remove gas on timescales comparable to the crossing times (Dekel & Silk 1986).

The increase in color dispersion with galaxy M_B also implies an increased metallicity spread. A simple closed-box chemical evolution model matches the color distribution for all the dEs fairly well if the effective yield is $p = 0.03Z_{\odot}$. This is lower than typical supernovae yields and implies the closed-box model is not appropriate, a significant amount of gas must be lost due to winds (Lotz *et al.* 2004).

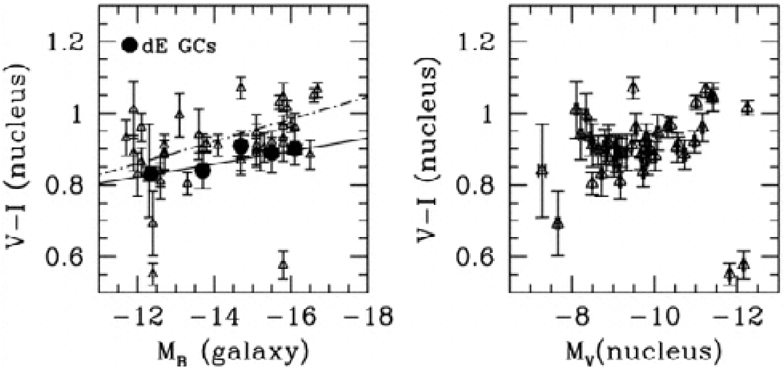

Figure 5. Colors of dE nuclei vs. galaxy M_B and the nuclei's M_V (from Lotz *et al.* 2004). Filled circles in the left panel are the mean GC colors and the dot-dashed line is the fit to the $(V - I)_{nuc} - M_B$ trend.

4. The Formation of GCs and Nuclei

The picture that emerges from several decades of work on GCs in dEs within 20 Mpc is that the GCs are older, more metal-poor, and more α-enhanced than the majority of the field stars within the galaxies. Both the GCs and the field stars show shallow trends of increasing mean metallicity with galaxy luminosity. The majority of the GCs in dEs have ages greater than 10 Gyr while about 25% have ages of about 6 Gyr or younger.

Mackey & Gilmore (2004) have done a detailed comparison of the GCs in Sagittarius and Fornax with the different GC populations of the Galaxy. Based on spatial distributions, kinematics, metallíticities, HB morphologies, core-radii distributions, and age distributions, the GCs in the dEs are most closely related to the "Young Halo" (YH) Galactic population. These are characterized by an extended spatial distribution, high velocity dispersion and no rotation, and low mean metallicities but HB morphologies that are too red for their metallicities (see Figure 3). Some "Young Halo" GCs are as old as the oldest "Old Halo" clusters but a high fraction have ages 2–4 Gyr younger than the oldest GCs, consistent with age being the dominant 2^{nd} HB parameter. Based on these similarities Mackey & Gilmore (2004) argue that up to 75% of the "Young Halo" GCs and 25% of the "Old Halo" GCs have origins in accreted dwarf galaxies.

We can use this information on GCs to develop a timeline of the early universe within the CDM paradigm. The first stellar system to form would be GCs within gas-rich fragments in the most massive dark matter halos. Over the next 1–3 Gyr GC formation begins in lower-mass halos that eventually become today's dwarf galaxies. The vigorous star formation at this time produces clusters with high [α/Fe]. Between reionization and supernovae winds that occur at this time vigorous star formation in dwarfs is squelched and cluster formation stops. After reionization at $z \sim 1$ ($t \sim 8$ Gyr) it becomes easier for gas to cool and star formation to resume. Random density fluctuations or interactions due to dwarfs falling into galaxy groups or clusters can then form a few new GCs that are enriched in [Fe/H] and have lower [α/Fe].

It has been shown that dE nuclei are closely related to GCs and so are likely form by similar processes. Nuclei can be just bright GCs but some can be distinguished by having large sizes for their luminosities and by not having simple stellar populations. Large GCs/nuclei may form near the centers of dwarfs because the densest gas collects at the centers of the potentials. As above, they would be likely to form early and so would be more metal-poor than most field stars. Massive GCs that don't form in the centers may quickly sink there as a result of dynamical friction (Lotz *et al.* 2001). Multiple populations can result from GC-GC mergers due to dynamical friction or from additional star formation from enriched gas.

More observational and theoretical work are needed to test and validate this picture and flesh out the details. Observationally, we should aim to get high signal-to-noise and high-resolution spectroscopy of all the remaining GCs in Local Group dEs in order to study abundance patterns. We are also working to get spectroscopy of the GCs in the Virgo and Fornax dEs in order to test our assumptions that they are old and compare them to Local Group dEs. GCs promise to continue to be some of our best fossils of the conditions in the early universe.

Acknowledgements

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Discussion

DRINKWATER: You mentioned that some of the nuclei were bluer. Could you elaborate on that and describe them?

MILLER: Two of the nuclei in Figure 5 have $V - I < 0.6$. This color is too blue to be explained by difference in metallicity so they must be extremely young, like the nucleus of NGC 205. One of these systems is FCC 46 which is discussed by Debattista in these proceedings.

MASHCHENKO: Is there a similar correlation between the metallicity of the GCs and the blue luminosity of the host galaxy for giant galaxies?

MILLER: Yes, Figure 4 shows that the color (or metallicity) - M_B trend for GCs dwarfs is consistent with the trend for the *blue* GCs in giant galaxies.