DAMP MERGERS: RECENT GASEOUS MERGERS WITHOUT SIGNIFICANT GLOBULAR CLUSTER FORMATION?

DUNCAN A. FORBES, ROBERT PROCTOR, JAY STRADER, AND JEAN P. BRODIE Centre for Astrophysics and Supercomputing, Swinburne University, Hawthorn, VIC 3122, Australia; and UCO/Lick Observatory, University of California, Santa Cruz, CA 95064; dforbes@astro.swin.edu.au Received 2006 September 20; accepted 2006 December 14

ABSTRACT

Here we test the idea that new globular clusters (GCs) are formed in the same gaseous ("wet") mergers or interactions that give rise to the young stellar populations seen in the central regions of many early-type galaxies. We compare mean GC colors with the age of the central galaxy starburst. The red GC subpopulation reveals remarkably constant mean colors independent of galaxy age. A scenario in which the red GC subpopulation is a combination of old and new GCs (formed in the same event as the central galaxy starburst) cannot be ruled out, although this would require an age-metallicity relation for the newly formed GCs that is steeper than the Galactic relation. However, the data are also well described by a scenario in which most red GCs are old, and few, if any, are formed in recent gaseous mergers. This is consistent with the old ages inferred from some spectroscopic studies of GCs in external systems. The event that induced the central galaxy starburst may have therefore involved insufficient gas mass for significant GC formation. We term such gas-poor events "damp" mergers.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: interactions — globular clusters: general

Online material: color figures

1. INTRODUCTION

Since the first hints that the color distributions of globular cluster (GC) systems in some early-type galaxies were bimodal (Couture et al. 1991; Ashman & Zepf 1992), bimodality has been shown to be the norm (e.g., Larsen et al. 2001; Kundu & Whitmore 2001; Strader et al. 2006; Peng et al. 2006). This blue/red bimodality indicates distinct metallicity (and perhaps age) subpopulations within the GC system. The mean color of the blue and red subpopulations are known to correlate with their host galaxy luminosity (Strader et al. 2004). Basic interpretations of these two subpopulations include dissipative formation at early epochs (Forbes et al. 1997), gaseous mergers at early or late epochs (Ashman & Zepf 1992), and the dissipationless accretion of GCs (Cote et al. 2002). A key piece of evidence in assessing these scenarios is the age distribution of the two GC subpopulations. The current state of affairs is summarized in the review of Brodie & Strader (2006), which notes that small spectroscopic samples to date find most GCs to be $\gtrsim 10$ Gyr old, implying an early formation epoch at redshifts $z \ge 2$. However, such work is limited by sampling biases: only the brightest GCs in nearby $(\leq 25 \text{ Mpc})$ galaxies can be studied. To create large samples of typical GCs, one must use photometric studies.

Many early-type galaxies are found to have younger central stellar populations, indicative of a recent interaction or gaseous ("wet") merger that induced some star formation (Trager et al. 2000; Proctor & Sansom 2002; Terlevich & Forbes 2002; Thomas et al. 2005; Denicolo et al. 2005; Sanchez-Blazquez et al. 2006, hereafter SB06).¹ The age of this young starburst has been found to correlate with a galaxy's location on the fundamental plane and with morphological fine structure (Schweizer & Seitzer 1992; Forbes et al. 1998b). There is also good evidence for the formation of proto-GCs in ongoing wet mergers such as the Antennae

(Whitmore & Schweizer 1995), which are thought to ultimately form an elliptical galaxy (e.g., Toomre & Toomre 1972). Furthermore, as star clusters appear to be the primary mode of star formation (Lada & Lada 2003), we expect GCs to trace major star formation episodes in all starbursts (Larsen & Richtler 2000). In the semianalytic models of Beasley et al. (2002) metal-poor GCs form in protogalactic fragments at high redshift, while metal-rich ones form in subsequent gas-rich merging events. However, if formation conditions are not suitable (e.g., insufficient gas mass or low GC formation efficiency), then few long-lasting GCs may be produced. Local examples of this include the Galaxy's disk and the LMC, which have experienced open cluster formation without GC formation. Also, in the case of gas-free ("dry") accretions or mergers, no induced star, or star cluster, formation is expected.

Major gaseous mergers (Ashman & Zepf 1992) are predicted to form new metal-rich GCs with a mean age corresponding to that of the merger. Any new GCs formed will add to the existing GC system of the progenitor galaxies, i.e., an old metal-poor (blue) and possibly an old but more enriched (red) subpopulation.

The newly formed metal-rich GC subpopulation will initially be very blue; however, it will redden rapidly (e.g., Whitmore et al. 1997). If formed in the last gigayear, the subpopulation may have a color similar to that observed for blue subpopulations in early-type galaxies. For the first couple of gigayears, depending on its metallicity, it may have intermediate colors. However, older than a few gigayears, the colors resemble those of red subpopulations and continue to redden slowly with age. If significant numbers of new GCs were formed more than a few gigayears ago, then the red subpopulation of the merger remnant galaxy may be dominated by these newly formed, metal-rich GCs. The mean color of the red subpopulation will therefore be determined by the relative fraction of newly formed versus old GCs and their respective enrichment levels (metallicity) and time elapsed (age) since formation.

Although broadband colors are subject to the age-metallicity degeneracy, the evolution of color for any reasonable GC metallicity

¹ In some low-mass galaxies, "cold" flows from the intergalactic medium may be a possible source of gas (e.g., Keres et al. 2005).

has a similar characteristic form and can be well described by a single stellar population model. Thus, we can model the expected mean color of the red subpopulation with age and compare this to the observed color and age of the galaxy's central starburst. Here we examine two relatively large samples of early-type galaxies in order to test the idea that the red subpopulation of GCs were largely formed in gaseous mergers (Ashman & Zepf 1992).

2. THE DATA

We present two data sets for which we have obtained GC colors and central starburst ages for the same galaxies. The first sample has been gathered from a wide variety of literature sources; we refer to this as our heterogeneous sample. The second sample comes from a single photometric source (the ACS Virgo Cluster Survey; Peng et al. 2006) and single galaxy age study (Caldwell et al. 2003); we refer to this as our homogeneous sample.

2.1. A Heterogeneous Sample: Galaxy Ages

Stellar age estimates based on an analysis of Lick absorption lines are available for a number of early-type galaxies. Such ages are luminosity weighted, and date the last major starburst while giving little information on the mass involved. They are also central values that may not therefore reflect the galaxy as a whole (see, e.g., discussion in Terlevich & Forbes 2002).

For our first sample of 36 galaxies, we take galaxy ages from four independent studies: Terlevich & Forbes (2002), Thomas et al. (2005), Denicolo et al. (2005), and SB06. All four employ a similar method of using the H β index and the [MgFe] composite index, together with a single stellar population (SSP) model, to derive galaxy ages and metallicities. In Table 1 we list the central ages from these four studies for those galaxies that also have GC colors available from the literature. When more than one age estimate is available, the agreement among studies is generally quite acceptable. For these galaxies we adopt the average age value. However, for four galaxies the estimates are wildly different.

The galaxies with discrepant age estimates are as follows:

NGC 1052.—We adopt the young age of Denicolo et al. (2005). This is supported by Pierce et al. (2005), who measured a galaxy age of \sim 2 Gyr.

NGC 1407.—We adopt the old age given by Thomas et al. (2005). This is supported by the high-quality spectra of Cenarro et al. (2007) and M. Spolaor et al. (2007, in preparation), which indicate very old central ages.

NGC 3115.—We adopt the age of SB06, but note that Norris et al. (2006) have shown that NGC 3115 has a younger age along the major than minor axis.

NGC 4365.—We adopt the 7.9 Gyr age of SB06, which is supported by the 9.7 Gyr age derived by Proctor & Sansom (2002). Our final adopted age is given in the last column of Table 1.

Using all the galaxies with multiple age estimates, we measure an average rms scatter of ± 0.2 dex in log age (ages are derived from SSP model grids that are nearly uniform in log), or ~2 Gyr. A further indication that our age estimates are reasonable is provided by Figure 1. Here we show the residual from the fundamental plane value for each galaxy (from Prugniel & Simien 1996) in log units against log of our adopted galaxy age for the available galaxies. The solid line is the fit from a much larger sample of Forbes et al. (1998b). The data scatter about the Forbes et al. fit line showing that the galaxy ages are related to an independently measured value, i.e., the deviation of the galaxy from the standard fundamental plane. The rms scatter in galaxy age is consistent with the value quoted above for age estimates between different studies.

TABLE 1 Galaxy Central Ages

Galaxy	TF02 (Gyr)	T05 (Gyr)	D05 (Gyr)	SB06 (Gyr)	Adopted (Gyr)
NGC 584	2.1	2.8	3.8	5.6	3.6
NGC 1052		21.7	2.9		2.9
NGC 1316	2.8	3.2			3.0
NGC 1374	9.8				9.8
NGC 1379	7.8				7.8
NGC 1380	6.2				6.2
NGC 1399	5.0				5.0
NGC 1404	5.0				5.0
NGC 1407		7.4	2.5		7.4
NGC 1427	6.5				6.5
NGC 1700	2.3	2.6	2.6	5.1	2.5
NGC 3115			2.6	8.4	8.4
NGC 3377	4.1	3.6	3.6	5.2	4.1
NGC 3379	9.3	10.0	10.9	8.2	9.6
NGC 3384			6.5		6.5
NGC 3610			1.8		1.8
NGC 3923		3.3	2.6		3.0
NGC 4278	8.4	12.0		12.4	10.9
NGC 4365			3.6	7.9	7.9
NGC 4374	11.0	12.8	3.8	11.2	11.7
NGC 4472	8.5	9.6		9.6	9.2
NGC 4494			6.7		6.7
NGC 4552	9.6	12.4		12.3	11.4
NGC 4594				10.0	10.0
NGC 4621				8.7	8.7
NGC 4636				10.0	10.0
NGC 4649	11.0	14.1			12.6
NGC 5322			2.4		2.4
NGC 5557			7.0		7.0
NGC 5846	12.0	14.2	10.2	8.4	11.2
NGC 5982			12.3		12.3
NGC 6702	1.9	1.7		1.6	1.7
NGC 6868	15.0				15.0
NGC 7332	4.5		1.0		2.8
NGC 7619	9.0	15.4	5.9		10.1
IC 4051	12.0	15.0			13.5

Finally, we note that excluding the four galaxies with the most discrepant ages in Table 1 from the analysis does not affect our results.

2.2. A Heterogeneous Sample: Globular Cluster V–I Colors

A large number of early-type galaxies have been imaged with sufficient precision to detect bimodality in the GC color distribution, particularly with the Hubble Space Telescope (HST). Although Advanced Camera for Surveys (ACS) imaging of GCs is becoming more common (e.g., Peng et al. 2006; Harris et al. 2006; Forbes et al. 2006; Strader et al. 2006; Spitler et al. 2006), most HST studies have used the Wide Field Planetary Camera 2. These latter data were typically taken in the V and I filters. We have searched the literature to compile a database of mean blue and red GC colors for early-type galaxies observed by HST or with ground-based telescopes. It excludes the recent ACS Virgo Cluster Survey, which is discussed in § 2.3. We do, however, include the Sombrero Sa galaxy, as it is extremely bulge dominated. We have transformed other filter combinations (i.e., mostly B-Iand C-T1 into V-I using the conversions of Forbes & Forte (2001). The conversion of Forbes & Forte (2001) is an empirical one based on the Galactic GC system, i.e., it assumes old stellar populations. A conversion for younger stellar populations would predict a bluer V-I color than an assumed old age. However, the differences are very small because the filters are similar to V-I



FIG. 1.—Residual from the fundamental plane vs. galaxy age. The deviation from the standard fundamental plane (Prugniel & Simien 1996) is plotted against our adopted galaxy age. The solid line is the fit from Forbes et al. (1998b) for a larger sample of elliptical galaxies. The sample used here follows the general Forbes et al. trend with a rms scatter in log age of 0.2 dex (or 1.6 Gyr).

and the age-metallicity degeneracy means tracks of different ages run roughly parallel to each other. This is illustrated in Figure 2, which shows Bruzual & Charlot (2003, hereafter BC03) SSP model tracks for single ages of 2 and 12.5 Gyr at various metallicities. Over the typical B-I color range of GCs (i.e., 1.5 <B-I < 2.2) the predicted V-I color is ≤ 0.03 mag redder if GCs are as young as 2 Gyr compared to our assumption of 12.5 Gyr. A similar offset occurs if C-TI is compared to V-I. As well as these filter transformations, we have applied extinction corrections from Schlegel et al. (1998) to all GC colors. In Table 2 for each galaxy with an age estimate, we list the $(V-I)_0$ colors after transformation from the original filter combination and extinction correction. We also give the original reference for the GC photometry, whether the bimodality is confirmed (Y) or likely (L), the original filter combination and whether the photometry comes from HST(Y) or not (N).²

The galaxies in this sample cover a range of luminosities, and GC colors are known to correlate with the luminosity of their host galaxy (see Brodie & Strader 2006 for a review). This correlation is thought to be largely a metallicity-mass relation. Before searching for any correlations of GC color with galaxy age, we have removed this effect using the observed GC V-I color–galaxy luminosity relations of Strader et al. (2004). This correction (of typically less than 0.05 mag) eliminates, at least to first order, any GC color variations due to the range of host galaxy luminosities in our sample.



FIG. 2.—Plot of V-I vs. B-I SSP models. From the SSP models of BC03 we show the single age tracks for a 12.5 Gyr old population (*solid line*) and a 2 Gyr population (*dashed line*). Six different metallicities from [Fe/H] = -2.3 to +0.4 dex are indicated. For typical B-I colors of GCs (i.e., 1.5 < B-I < 2.2) the predicted V-I color is ≤ 0.03 mag redder if GCs are as young as 2 Gyr compared to an assumption of 12.5 Gyr.

2.3. A Homogeneous Sample: Galaxy Ages

Central ages for 33 low-luminosity early-type Virgo galaxies are taken from a single source, i.e., Caldwell et al. (2003). We use their best-fit age, which comes from comparing high-order Balmer lines and Fe4383 with an SSP model. Using a single source avoids any systematic differences that may be present between multiple sources.

2.4. A Homogeneous Sample: Globular Cluster g-z Colors

Mean colors for the blue and red GC subpopulations of earlytype Virgo galaxies come from the ACS Virgo Cluster Survey of Peng et al. (2006). This data set has several advantages over the V-I colors from the literature; namely, g-z has twice the metallicity sensitivity of V-I, the photometric uncertainties are generally lower, and galaxies are at the same distance, so any potential aperture effects do not play a role. Uncertainties in the peak colors range from ± 0.01 to 0.3 mag. Following Peng et al. we assume m-M = 31.09 to the Virgo Cluster.

For VCC 1488 (IC 3487), the mean blue color listed in Peng et al. (2006) of g-z = 0.72 does not seem to correspond to the fitted Gaussians displayed in their Figure 2. In this case we have chosen to take the mean color for the blue GCs from the work of Strader et al. (2006). This value, of g-z = 0.82, better represents the color distribution. Finally, we correct all GC g-z colors using the GC color–galaxy luminosity relation of Peng et al. (2006).

3. RESULTS AND DISCUSSION

² A complete table of GC photometry (i.e., including those galaxies without age estimates) can be found at http://astronomy.swin.edu.au/dforbes/colors.html.

Having described the data from which we take GC mean subpopulation colors and central galaxy ages, we now present our

TABLE 2 Globular Cluster Mean Colors

Galaxy	Туре	M_V	Blue $(V-I)_0$	Error	Red $(V-I)_{o}$	Error	Reference	Bimodal	Filter	HST?
N0584	E4	-21.40	0.96	0.05	1.16	0.05	K01	L	V-I	Y
N1052	E4	-20.99	0.90	0.10	1.08	0.10	F01	Y	B-I	Ν
N1316	S0p	-22.79	0.90	0.03	1.03	0.03	G04b	Y	V-I	Y
N1374	EÎ	-20.40	0.94	0.05	1.15	0.05	B06	Y	C-TI	Ν
N1379	E0	-20.66	0.95	0.05	1.13	0.05	B06	Y	C-TI	Ν
N1380	SO	-21.70	0.87	0.10	1.16	0.10	K97	Y	B-R	Ν
N1399	cD	-21.85	0.96	0.03	1.16	0.03	F98	Y	B-I	Y
N1404	E1	-21.41	0.91	0.03	1.17	0.03	F98	Y	B-I	Y
N1407	E0	-20.87	0.93	0.02	1.16	0.02	F06	Y	B-I	Y
N1427	E5	-20.49	0.97	0.10	1.17	0.10	F01	Y	C-TI	Ν
N1700	E4	-22.49	0.90	0.10	1.12	0.10	B00	Y	B-I	Ν
N3115	SO	-20.84	0.92	0.05	1.15	0.05	L01	L	V-I	Y
N3377	E5	-19.79	0.93	0.05	1.10	0.05	K01	L	V-I	Y
N3379	E1	-20.69	0.96	0.05	1.17	0.05	L01	L	V-I	Y
N3384	SB0	-20.13	0.94	0.05	1.21	0.05	L01	L	V-I	Y
N3610	E5	-21.35	0.94	0.03	1.16	0.03	W02	Y	V-I	Y
N3923	E4	-21.92	1.00	0.10	1.20	0.10	Z95	Y	C-TI	Ν
N4278	E1	-21.11	0.92	0.05	1.12	0.05	K01	L	V-I	Y
N4365	E3	-21.41	0.98	0.03	1.19	0.03	L01	L	V-I	Y
N4374	E1	-20.92	0.91	0.03	1.07	0.06	G04a	Y	B-R	Ν
N4472	E2	-22.81	0.94	0.03	1.21	0.03	L01	Y	V-I	Y
N4494	E1	-22.00	0.90	0.03	1.10	0.03	L01	Y	V-I	Y
N4552	E5	-21.24	0.95	0.03	1.17	0.03	L01	Y	V-I	Y
N4594	Sa	-22.00	0.94	0.03	1.18	0.03	L01	Y	V-I	Y
N4621	E5	-21.33	0.95	0.03	1.13	0.03	K01	Y	V-I	Y
N4636	Е	-20.58	0.95	0.02	1.19	0.02	D05	Y	C-TI	Ν
N4649	E2	-22.40	0.95	0.03	1.21	0.03	L01	Y	V-I	Y
N5322	E3	-22.09	0.96	0.03	1.14	0.03	H06	Υ	B-I	Y
N5557	E1	-22.24	0.96	0.03	1.18	0.03	H06	Υ	B-I	Y
N5846	E0	-22.23	0.94	0.03	1.15	0.03	F97	Y	V-I	Y
N5982	E3	-21.80	0.97	0.05	1.16	0.05	K01	L	V-I	Y
N6702	Е	-21.98	0.83	0.10	1.16	0.10	G01	Y	B-I	Ν
N6868	Е	-22.17	0.91	0.07	1.12	0.07	D02	Y	B-R	Ν
N7332	S0p	-20.09	0.88	0.10	1.08	0.10	F01	L	B-I	Ν
N7619	E2	-22.12	0.99	0.03	1.24	0.03	L00 ^a	Y	V-I	Y
I4051	Е	-21.75	0.98	0.05	1.16	0.05	$L00^{a}$	L	V-I	Y

^a S. Larsen 2000, private communication.

results. As well as the color of the red subpopulation we show results for the color difference between the red and blue subpopulations. A variety of observational and theoretical work suggests that blue GCs may have been formed before reionization at $z \ge 6$. This implies ages of ≥ 12.7 Gyr. Such old ages are reflected in the observed near constant color of blue GC subpopulations. The color difference is therefore largely due to the age and metallicity of the red GCs, and it may be more accurately determined than the individual subpopulation mean colors.

Figure 3 shows the mean V-I and g-z colors of the red GC subpopulations, and the color difference between red and blue subpopulations versus galaxy stellar age for our two samples. The GC colors in this, and subsequent figures, have been corrected for the GC color–galaxy luminosity relation as described above.

For the heterogeneous sample we find constant V-I colors with an rms spread of 0.044 mag, or an error on the mean for 36 galaxies of 0.007 mag. For the homogeneous sample we find constant g-z colors with an rms spread of 0.068 mag, or an error on the mean for 33 galaxies of 0.012 mag. The rms scatter is equal to, or less than, the typical photometric errors in our samples, suggesting that the intrinsic scatter is indeed very low.

In Figure 3 we use different symbols within the heterogeneous sample when the bimodality is classified as confirmed (Y) or

likely (L) in Table 2. The figure shows that there is no systematic offset between the two classifications of bimodality; for subsequent figures we use a single symbol for the heterogeneous sample. An analysis of a subsample of the ACS Virgo Cluster Survey was first carried out by Strader et al. (2006). A comparison of their sample with that from Caldwell et al. (2003) reveals 12 galaxies in common with GC color and galaxy age measurements. We have examined them in a similar way to above, finding constant g-z colors, i.e., an rms scatter of 0.059 and an error on the mean of 0.017 mag.

In this and subsequent figures we show evolutionary tracks based on SSP models from Bruzual & Charlot (2003), which assume a Salpeter initial mass function and a solar abundance ratios (we note that other SSP models give similar results).

The track in Figure 3 is the scenario in which *all* red GCs are uniformly old with a fixed metallicity of [Fe/H] = -0.7, and hence the evolutionary track has a constant color. This is the scenario in which no GCs formed at the time of the central starburst so that GC color is unrelated to galaxy age. We call this the no evolution (NE) track, and it provides a good fit to the mean color of the red subpopulation. For the color difference between the red and blue subpopulations we have simply shifted the NE track bluer by an arbitrary amount. Again, it provides a good representation of the data.



Fig. 3.—Mean GC colors vs. central galaxy age for early-type galaxies. The squares (bimodal = yes) and circles (bimodal = likely) show the mean colors of the red GC subpopulation, and the triangles show the color difference between the red and blue subpopulations. The GC colors have been corrected for the GC color–galaxy luminosity relation. The solid lines show the predicted color for a 12.5 Gyr old [Fe/H] = -0.7 SSP, called the NE track. The data are consistent with having a constant color, and hence the NE track. [See the electronic edition of the Journal for a color version of this figure.]

Although the scenario in which all of the red GCs are old (with none forming in recent mergers) is a good fit to the observed data, can other scenarios be ruled out?

Figure 4 shows the predicted change in color for a fixed metallicity (FM) of [Fe/H] = -0.7. This track corresponds to the situation in which *all* red GCs in a galaxy formed at the time of the central galaxy starburst with a metallicity of [Fe/H] = -0.7(i.e., the metallicity required for very old GCs to be consistent with their measured colors). It provides a plausible fit to the data at old ages but deviates strongly from the data for young ages. Lower metallicity tracks would provide a worse fit at all ages. Higher metallicity (e.g., solar) tracks could explain the GC colors in the youngest galaxies but would fail to match the color of the oldest galaxies. Thus, we can fairly confidently rule out the scenario in which all red GCs were formed in a merger from gas of a FM over a wide range of epochs.

A more plausible scenario is that the gas from which GCs form is steadily enriched over time, so the oldest red GCs may have formed from [Fe/H] = -0.7 gas (to match the observed color), but younger GCs, forming more recently, would be more metalrich. Thus, we need to assume a relationship for the enrichment of the gas with time (age) as the universe evolves. A plausible agemetallicity relation comes from the fossil record of the Galactic



FIG. 4.—Mean GC colors vs. central galaxy age for early-type galaxies. Symbols same as in Fig. 2. The solid lines show the predicted color evolution for a fixed metallicity of [Fe/H] = -0.7, called the FM track. The data are inconsistent with the FM track. [See the electronic edition of the Journal for a color version of this figure.]

disk. From studies of individual stars and star clusters, Edvardsson et al. (1993) found that a simple linear relation between metallicity and log age is a reasonable fit to the data (albeit with some scatter). Thus, for this scenario we assume *all* red GCs formed at the time of the central galaxy starburst with a metallicity determined by the Galactic age-metallicity relation. Figure 5 shows this mixed metallicity (MM) evolutionary track. This track provides a good fit to the majority of the data. A fit of the data points to the MM track gives an rms of 0.056 for the heterogeneous sample and 0.077 for the homogenous sample, i.e., similar to that of the NE track. A slightly steeper age-metallicity relation (producing redder GCs at a given age) would provide a better fit; conversely, a shallower age-metallicity would provide a worse fit to the data.

The MM track assumes 100% of the red GCs are formed at the time of the recent central starburst. A contribution of old, metalrich red GCs from the progenitor galaxies will tend to "dilute" the track, making it more similar to the NE track of Figure 3. Perhaps a good illustration of this is the young merger remnant NGC 3610 in our heterogeneous sample. This galaxy has a central starburst age of ~1.8 Gyr. Strader et al. (2004) obtained spectra of 10 red GCs and found only two to have an age consistent with forming at the same time as the galaxy starburst. If these 10 GCs are representative, then 80% of the red GC subpopulation is old and 20% formed in a gaseous merger event ~1.8 Gyr ago. The red GC subpopulation has a mean V-I color that is



FIG. 5.—Mean GC colors vs. central galaxy age for early-type galaxies. Symbols same as in Fig. 2. The solid lines show the predicted color evolution for an age-metallicity relation based on the Galactic disk (see text for details), called the MM track. The data are consistent with the MM track. [*See the electronic edition of the Journal for a color version of this figure.*]

consistent not only with the pure NE track but also with one that contains a 20% contribution from our MM track. Thus, a contribution of old and newly formed red GCs can account for the observed GC colors in the youngest galaxies if the age-metallicity relation is not shallower than assumed.

4. CONCLUDING REMARKS

We have compared the observed mean color of the red GC subpopulation and its color difference with the blue subpopulation to the age of the central starburst for two samples of early-type galaxies. We find that, for both samples, the GC subpopulation colors show no trend with galaxy age and effectively have a constant value. To interpret this result, three evolutionary scenarios are discussed. A fixed metallicity (FM) for newly formed red GCs is a poor representation of the data, especially for young galaxy ages. A mixed metallicity (MM) scenario (in which the younger GCs form from progressively more metal enriched gas) provides a better fit to the data. The fit can be improved with a steeper age-metallicity relation than we have assumed and/or a significant contribution from old GCs to the red GC subpopulation in young galaxies; a shallower age-metallicity relation is inconsistent with the data. A good fit to the data is provided by a no evolution scenario in which most of the red GCs are uniformly old, and few, if any, formed in late epoch gaseous mergers.

This latter conclusion supports some previous spectroscopic work that most GCs in elliptical galaxies are old, and that few new GCs survive from the same gaseous merger event that gave rise to the central young starburst. There are several possible interpretations: (1) proto-GCs formed but were quickly destroyed; (2) GCs formed with unexpectedly low efficiency in major starforming events; or (3) the starburst involved little gas mass, and so few new stars and GCs were formed. We term the latter gaspoor events "damp" mergers. If situations (1) and (2) can be ruled out by studies of nearby ongoing mergers, then the our results would be more consistent with frosting models (e.g., Trager et al. 2000) than with quenching models (Faber et al. 2005) for earlytype galaxies.

We acknowledge Francois Schweizer for making the initial suggestion that motivated this work. We thank the referees for several useful comments that have improved this paper. This material is based on work supported by the Australian Research Council and the National Science Foundation under grant AST 05-07729.

REFERENCES

- Ashman, K., & Zepf, S. 1992, ApJ, 384, 50
- Bassino, L., Richtler, T., & Dirsch, B. 2006, MNRAS, 367, 156 (B06) Beasley, M. A., Baugh, C. M., Forbes, D. A., Sharples, R. M., & Frenk, C. S.
- 2002, MNRAS, 333, 383
- Brodie, J., & Strader, J. 2006, ARA&A, 44, 193
- Brown, R., Forbes, D., Kissler-Patig, M., & Brodie, J. 2000, MNRAS, 317, 406 (B00)
- Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000 (BC03)
- Caldwell, N., Rose, J., & Concannon, K. 2003, AJ, 125, 2891
- Cenarro, J., et al. 2007, AJ, submitted
- Cote, P., West, M., & Marzke, R. 2002, ApJ, 567, 853
- Couture, J., Harris, W., & Allwright, J. 1991, ApJ, 372, 97
- Da Rocha, C., Mendes de Oliveira, C., Bolte, M., Ziegler, B., & Puzia, T. 2002, AJ, 123, 690 (D02)
- Denicolo, G., Terlevich, R., Terlevich, E., Forbes, D., & Terlevich, A. 2005, MNRAS, 358, 813 (D05)
- Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D., & Nissen, P. 1993, A&A, 275, 101
- Faber, S., et al. 2005, ApJ, submitted (astro-ph/0506044)
- Forbes, D., Brodie, J., & Grillmair, C. 1997, AJ, 113, 1652 (F97)
- Forbes, D., & Forte, J. 2001, MNRAS, 322, 257
- Forbes, D., Georgakakis, A., & Brodie, J. 2001, MNRAS, 325, 1431 (F01)

- Forbes, D., Grillmair, C., Williger, G., Elson, R., & Brodie, J. 1998a, MNRAS, 293, 325 (F98)
- Forbes, D., Ponman, T., & Brown, R. 1998b, ApJ, 508, L43
- Forbes, D., Sanchez-Blazquez, P., Phan, A., Brodie, J., Strader, J., & Spitler, L. 2006, MNRAS, 366, 1230 (F06)
- Georgakakis, A., Forbes, D., & Brodie, J. 2001, MNRAS, 324, 785 (G01)
- Gomez, M., & Richtler, T. 2004, A&A, 415, 499 (G04a)
- Goudfrooij, P., Gilmore, D., Whitmore, B. C., & Schweizer, F. 2004, ApJ, 613, L121 (G04b)
- Harris, W., Whitmore, B., Karakla, D., Okon, W., Baum, W., Hanes, D., & Kavelaars, J. J. 2006, ApJ, 636, 90 (H06)
- Keres, D., Katz, N., Weinberg, D., & Dave, R. 2005, MNRAS, 363, 2
- Kissler-Patig, M., Richtler, T., Storm, M., & Della Valle, M. 1997, A&A, 327, 503 (K97)
- Kundu, A., & Whitmore, B. 2001, AJ, 121, 2950 (K01)
- Lada, C., & Lada, E. 2003, ARA&A, 41, 57
- Larsen, S., Brodie, J., Huchra, J., Forbes, D., & Grillmair, C. 2001, AJ, 121, 2974 (L01)
- Larsen, S., & Richtler, T. 2000, A&A, 354, 836
- Norris, M., Sharples, R., & Kuntschner, H. 2006, MNRAS, 367, 815
- Peng, E., et al. 2006, ApJ, 639, 95
- Pierce, M., et al. 2005, MNRAS, 358, 419

- Proctor, R., & Sansom, A. 2002, MNRAS, 333, 517
- Prugniel, P., & Simien, F. 1996, A&A, 309, 749
- Sanchez-Blazquez, P., Gorgas, J., Cardiel, N., & Gonzalez, J. J. 2006, A&A, 457, 809 (SB06) Schlegel, D., Finkbeiner, D., & Marc, D. 1998, ApJ, 500, 525
- Schweizer, F., & Seitzer, P. 1992, AJ, 104, 1039 Spitler, L., et al. 2006, AJ, 132, 1593
- Strader, J., Brodie, J., & Forbes, D. 2004, AJ, 127, 295
- Strader, J., Brodie, J., Spitler, L., & Beasley, M. 2006, AJ, 132, 2333
- Terlevich, A., & Forbes, D. 2002, MNRAS, 330, 547 (TF02)
- Thomas, D., Maraston, C., Bender, R., & de Oliveira, C. M. 2005, ApJ, 621, 673 (T05)
- Toomre, A., & Toomre, J. 1972, ApJ, 178, 623 Trager, S., Faber, S., Worthey, G., & Gonzalez, J. 2000, AJ, 119, 1645
- Whitmore, B., Miller, B., Schweizer, F., & Fall, M. 1997, AJ, 114, 1797 Whitmore, B., & Schweizer, F. 1995, AJ, 109, 960
- Whitmore, B., Schweizer, F., Kundu, A., & Miller, B. 2002, AJ, 124, 147 (W02)
- Zepf, S., Ashman, K., & Geisler, D. 1995, ApJ, 443, 570 (Z95)