THE ASTROPHYSICAL JOURNAL, 441:120–128, 1995 March 1

GLOBULAR CLUSTER SYSTEMS IN THREE cD GALAXIES WITHIN RICH ABELL CLUSTERS

WILLIAM E. HARRIS[1]
Department of Physics and Astronomy, McMaster University, Hamilton, Ontario, Canada L8S 4M1
CHRISTOPHER J. PRITCHET[1]
Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada V8W 3P6
AND
ROBERT D. MCCLURE[1]
Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, 5071 West Saanich Road, Victoria, BC, Canada V8X 4M6
Received 1994 February 14; accepted 1994 September 9

ABSTRACT

We present new CCD photometry from the CFH telescope for three cD galaxies that are the centrally dominant objects in the rich Abell clusters A2052, A2107, and A2666. Photometry to $I(\text{lim}) = 25.0$ reveals the existence of globular cluster populations around all three of these: the first two appear to have M87-like high specific frequencies around $S_N \simeq 16$, but the third has a normal or subnormal value $S_N \simeq 3$. With these new data, globular cluster systems have now been searched for in a total of 12 centrally dominant cD galaxies in a wide range of galaxy clusters. We find that neither S_N nor the cluster population are correlated with any known property of the hot intracluster gas that usually surrounds such galaxies (cooling flow rate, gas temperature, total X-ray luminosity, etc.). From this, we conclude that cooling flows at the present epoch (i.e., in the last few Gyr) have little or nothing to do with globular cluster formation. The recently formed globular clusters in the central regions of such galaxies as NGC 1275 seem, instead, to be the result of occasional starburst phenomena. The vastly larger old-cluster populations filling the outer halos of many cD galaxies must be the result of an intensive phase of cluster formation during the very early protogalactic epoch.

Subject headings: galaxies: clusters: general — galaxies: elliptical and lenticular, cD — galaxies: star clusters

1. INTRODUCTION

The *specific frequency* S_N for a given galaxy is the number of globular clusters per unit ($M_V = -15$) galaxy luminosity (Harris & van den Bergh 1981; Harris 1991), and is a relatively easily measured ratio which represents the global efficiency of globular cluster formation over the history of the parent galaxy. In the so-called "high-S_N" globular cluster systems (GCSs) that are found in a few giant elliptical galaxies, S_N is about three times larger than the normal for E galaxies in rich environments like the Virgo Cluster, and almost an *order of magnitude larger* than in E galaxies that are located in the "field" or sparse groups.

Understanding the origin of the outstanding high-S_N GCSs—or indeed, the huge observed range of globular cluster populations that occur in otherwise similar galaxies—is still an open question. So far, the few known high-S_N cases are all *centrally dominant* galaxies in rich clusters, and all have extended cD-type envelopes to some degree. These include M87 in Virgo (McLaughlin, Harris, & Hanes 1983, 1994a), NGC 1399 in Fornax (Bridges, Hanes, & Harris 1991), NGC 3311 in Hydra (Harris, Smith, & Myra 1983; McLaughlin et al. 1995), and perhaps NGC 4874 in Coma (Harris 1987; Thompson & Valdes 1987). However, the central dominance within a galaxy's environment is clearly not a sufficient condition for generating a large GCS: Pritchet & Harris (1990) found that the extreme cD NGC 6166, the central object in the very rich A2199 cluster, has a normal or even subnormal S_N; and NGC 3842, by far the largest E galaxy in A1367, also appears to have a specific frequency not much above the normal level (Butterworth & Harris 1992). Recently, Bridges & Hanes (1994) have found that the central cD galaxy in the sparser cluster MKW 4 has a normal or slightly subnormal value $S_N \simeq 4$, and that the central giant E's in the small clusters AWM 2 and AWM 3 have even smaller GCSs ($S_N \lesssim 4$). Thus the data that exist so far suggest that the cause of the cD phenomenon and the buildup of a centrally dominant giant E galaxy in its environment is at least partly disconnected from globular cluster formation as such. So far, however, only a few centrally dominant galaxies have been searched for GCSs, and more obvious correlations of GCS size with other characteristics of the host galaxy or surrounding cluster might emerge with a larger sample size.

Continuing advances in imaging technology on large ground-based telescopes have made it possible to explore the GCS populations of increasingly distant galaxies and thus to extend our GCS search technique to new limits. In this paper we present new data for three cD galaxies selected from the sample of Malumuth & Kirshner (1985): NGC 7768 in A2666, at a redshift $cz = 7950$ km s^{-1}; UGC 9799 in A2052, at $cz = 10{,}440$ km s^{-1}; and UGC 9958 in A2107, at $cz = 12{,}630$ km s^{-1}. All three are centrally dominant objects with cD envelopes and in rich Abell clusters; the most distant (A2107) is nearly twice as far away as the Coma Cluster. Each one is ~0.5 mag more luminous than M87 (see Table 1) and thus is near the very top end of the galaxy mass distribution. In galaxies this distant, only the bright end of the globular cluster luminosity function (GCLF) is resolvable as a sprinkling of very faint, starlike objects concentrated toward the center of the cD. In the Virgo ellipticals (Harris et al. 1991), the globular clusters first appear at a magnitude level $B \simeq 21.2$ (depending only slightly on the total population size for galaxies this large), and their numbers rise steeply to fainter levels past that point. For

[1] Visiting observer at the Canada-France-Hawaii Telescope, which is operated by NRC of Canada, CNRS of France, and the University of Hawaii.

a target cD galaxy at $cz \sim 10{,}000$ km s^{-1}, about 4.5 mag more distant than Virgo, we would then expect to see this steep onset of the GCLF starting at $B \simeq 25.7$ (or $I \simeq 24.0$; see § 3). The limit of our photometry would then need to be ~ 1 mag fainter than that in order to define the appearance of the GCLF unambiguously. These goals press the limits of current ground-based imaging techniques.

In § 2 below, we discuss our new imaging data for the three cD galaxies; § 3 contains an analysis of the derived GCLFs and spatial structures of their cluster systems; and § 4 describes our estimates of S_N. In § 5 we summarize the available GCS data for all centrally dominant E or cD galaxies in which such surveys have been made, and correlate them with characteristics of the X-ray halo gas (temperature, luminosity, cooling flow rate, etc.) that have been suggested to relate to the globular cluster formation process. A preliminary report on these results was given in Harris, Pritchet, & McClure (1993).

2. OBSERVATIONS AND DATA REDUCTION

To obtain the necessary deep imaging data for our target galaxies, we used the High Resolution Camera (HRCam; McClure et al. 1989) at the prime focus of the Canada-France-Hawaii Telescope during an observing run in 1990 June. The camera was employed with the SAIC CCD detector (1024^2 format, image scale 0".13 pixel^{-1} with HRCam); since this is a red-sensitive chip, we chose to obtain I-band images, in each case for one field centered on the target galaxy. Total exposure times were 14×1000 s for A2052, 12×1000 s for A2107, and 6×1000 s for A2666. In addition, we acquired a 7×1000 s series for a "blank" control field near another cluster, Abell 2366, which is at nearly the same Galactic latitude as A2052 and A2107. This control field was used to help determine the background level of detected starlike images in each of our three cD program fields.

For each galaxy, the individual CCD frames were first binned 2×2, then registered to within ± 0.1 pixel and combined; for all four fields the stellar images had a mean FWHM near 2.5 binned pixels (0".6–0".7). The photometry of the final images was carried out by an iterative process of detecting and removing all starlike images on the frames through the IRAF implementation of DAOPHOT (Stetson 1987), coupled with median filtering to remove the underlying galaxy light (see Fischer et al. 1990 and Butterworth & Harris 1992 for more detailed descriptions of this procedure). The object detection threshold for the final FIND/PHOT/ALLSTAR passes was set at $\simeq 3.0$–3.5 times the standard deviation of the sky background in the outskirts of the fields.

Calibration of our I-band CCD photometry was accomplished by transfers from the NGC 4147 and M92 standard-star fields (Christian et al. 1985) and selected equatorial standards (Landolt 1983), exposures of which were taken frequently during the observing run. Large-aperture measurements of the standards yielded transformations of the form $i = I + 0.08X - 0.02(V-I) + \text{const}$, where i is the instrumental (DAOPHOT) magnitude and X the air mass. Since the color coefficient proved to be quite small, we simply adopted $(V-I) = 1.0$ as a mean color appropriate to globular clusters to calculate the zero-point correction $(I - i)$ needed for each program field.

Since the objects we are attempting to detect (the globular clusters around the cD's) appear starlike and extremely faint, we carried out extensive artificial-star tests with DAOPHOT/ADDSTAR to derive the image detection completeness and to correct for systematic photometric errors that usually arise near the faint limit of the data. In addition, image classification (with a modification of the Kron r_{-2} image moment; see Harris et al. 1991 for its definition and implementation) was done to sort out clearly nonstellar objects from the detection lists and thus substantially reduce the background "noise" in the residual object counts. Because the stellar FWHM was very similar on all our averaged frames, we used exactly the same r_{-2} cutoff values for each of them to ensure homogeneous classification boundaries.

Since both the level of image crowding and the background noise increase inward toward the galaxy center on each field, the photometric detection completeness should in principle be a function of location on the frame. The three cD's are ellipsoidal in shape by various amounts, so we chose to calculate the detection completeness as a function of local *sky background intensity* rather than just radius. We defined zones of specified surface brightness range and then measured the detection completeness f as a function of magnitude within each (roughly ellipsoidal) zone. In practice, we carried this procedure inward only to the point where the galaxy isophotal intensity was about 50% that of the sky background (typically at about 15" radius); closer to the center, the galaxy surface brightness increases dramatically and the data were no longer useful. For the outer zones that we used (excluding only these very central regions), the completeness fractions proved to change very little with location. In our four measured fields (i.e., the three cD galaxies plus the remote A2366 background field), the $f = 0.5$ completeness level occurred typically at $I = 24.6 \pm 0.2$, though we extended the luminosity function calculation down to $f \simeq 0.3$ (corresponding to $I = 25.0$ for A2052 and A2107, or $I = 24.8$ for A2666).

Last, we tested for the presence of "false" image detections generated purely by background noise (random clumps of brighter than average pixels). This was done in the same manner as described in Harris et al. (1991): the intensity value of each pixel was reflected about the mean sky level so that positive values became negative and vice versa, and this inverted picture was put through exactly the same reduction steps (any detected objects on this picture will by definition then be due to pure noise). After rejecting objects fainter than $I = 25$, and nonstellar objects according to the r_{-2} moment calculation, only a dozen false detections remained scattered randomly across the picture, and thus had completely negligible effects.

3. LUMINOSITY FUNCTIONS AND RADIAL DISTRIBUTIONS

For distant galaxies, a globular cluster system shows up as an excess of starlike images concentrated toward the galaxy center. We attempted to set the background number density in two independent ways: (1) by using the outer parts of each galaxy field itself, that is, the zone farther than $\simeq 1'$ from galaxy center; and (2) by using the remote control field, after second-order corrections for Galactic latitude (this was done by interpolation within a Galactic starcount model developed by one us (CJP); for small steps in latitude, the changes in star-count level are also well described by a simple cosecant law). Method (1) should provide a slight *overestimate* of the true background level, since a 1' radius from the galaxy center corresponds to a linear radius of $\simeq 30$ kpc at 100 Mpc distance, and in giant ellipticals the GCS often extends detectably beyond that projected radius (cf. Harris 1986; McLaughlin et al. 1993). Method (2) should actually be an *underestimate* of the true background

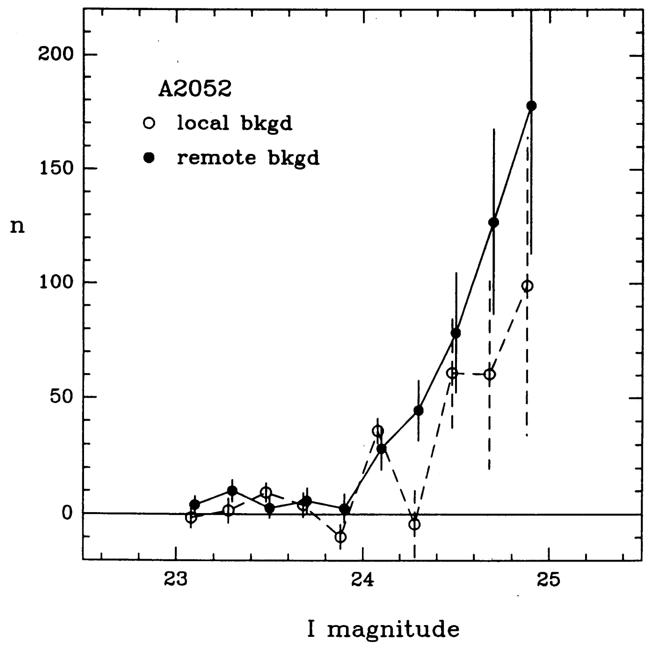

FIG. 1*a*

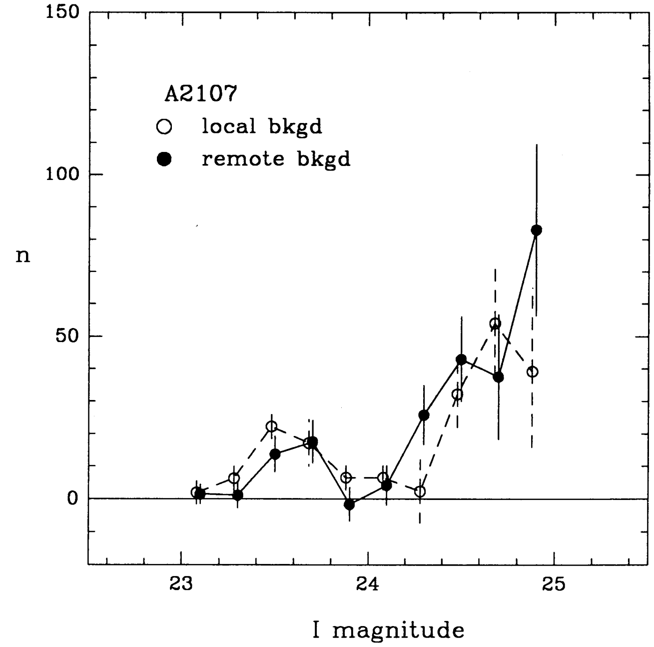

FIG. 1*b*

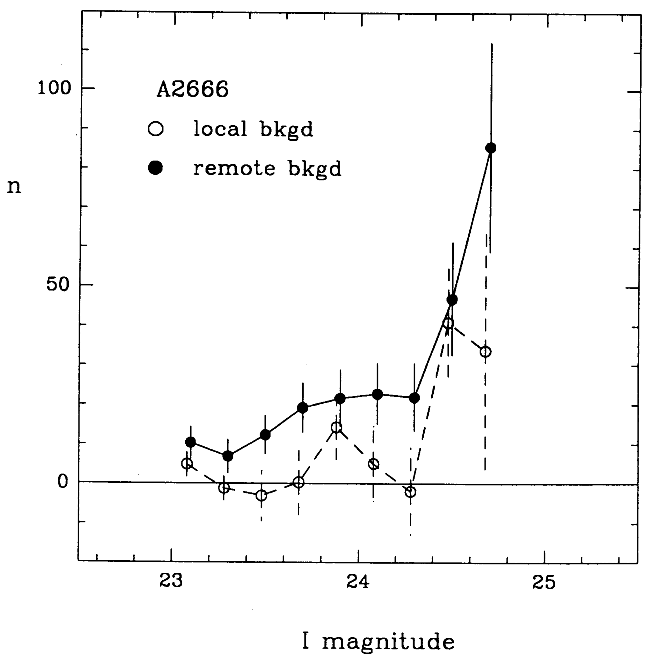

FIG. 1*c*

FIG. 1.—Luminosity functions for the starlike images in the field of each cD galaxy, after correcting for detection incompleteness, systematic photometric error, and subtraction of background counts. Detectably nonstellar images have been removed from both the galaxy and background counts as described in § 3. (*a*) The number of excess starlike objects for the A2052 field is plotted per 0.2 mag bin as a function of *I* magnitude. *Filled circles:* GCLF derived by using the "remote" CCD field to set the background LF (a blank control field far from A2052 but at the same Galactic latitude; see text). *Open circles:* GCLF derived by using the outer parts of the A2052 field itself ($r \gtrsim 1'$) to set the background LF. (*b*) The same data for the A2107 field. (*c*) The same data for the A2666 field. This field is at a much different Galactic latitude than the control background field, and the latitude normalization of the background LF is much more uncertain than in the previous figures.

even if the latitude normalization is correct, because it will not account for any extra population of faint dwarf galaxies clustered around the cD galaxy which may have crept through the image classification process.

After background removal, correction for detection incompleteness, correction for systematic photometric error following the results of the ADDSTAR tests, we found excess populations of starlike images concentrated around all three of the cD's. The luminosity functions of the residual populations, binned in 0.2 mag steps, are displayed in Figure 1. The most important single result from these graphs is their steep upturn in the luminosity function near $I \gtrsim 24$. This feature occurs just where it would be expected if it is simply the bright end of a globular cluster population similar to those found in the Virgo giant ellipticals. Comments on the individual fields follow:

A2052 (*panel a*)—For $I < 24$, there is no significant residual population, and no difference between the "local" versus "remote" background solutions. For $I > 24$, the remote-background solution yields excess population totals that are almost a factor of 2 higher by comparison, suggesting either that the globular cluster system extends spatially beyond the edges of our field, or that the central region of the A2052 cluster has a large population of low-luminosity dwarf galaxies that are nearly starlike at 1″ resolution (although such dwarfs would have to have linear diameters less than 500 pc for that to be the case), or some combination of the two. We suspect the first option is likely to be the dominant effect, given the characteristically shallow radial profiles of the GCSs in giant E and cD galaxies (see the discussion of the radial distributions below, and Harris 1986).

A2107 (*panel b*)—The appearance of the residual LF is similar to that for A2052, except that a small excess "bump" also appears around $I \simeq 23.5$. At the distance of A2107, this would correspond to $M_V \simeq -12$, which is at the right luminosity level to represent a small dwarf-elliptical population. The objects in this magnitude range ($23.2 < I < 24.0$), when

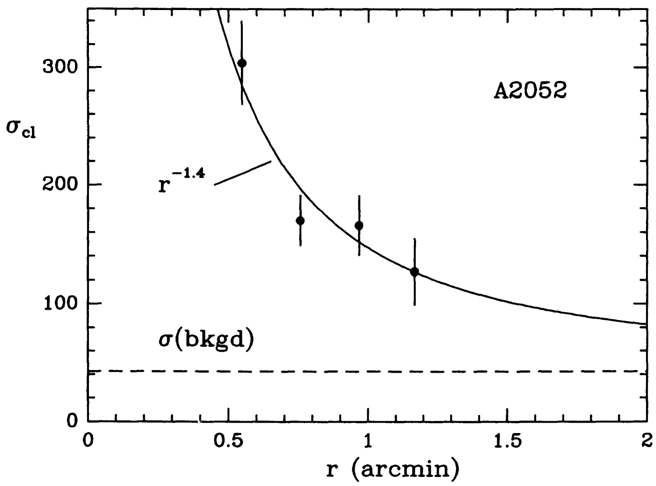

FIG. 2*a*

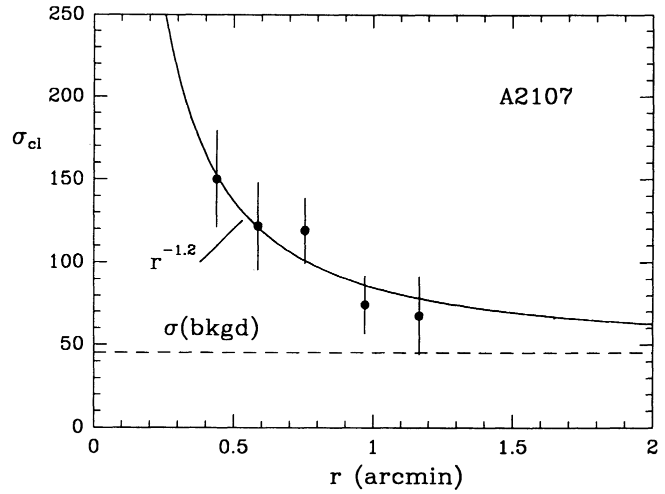

FIG. 2*b*

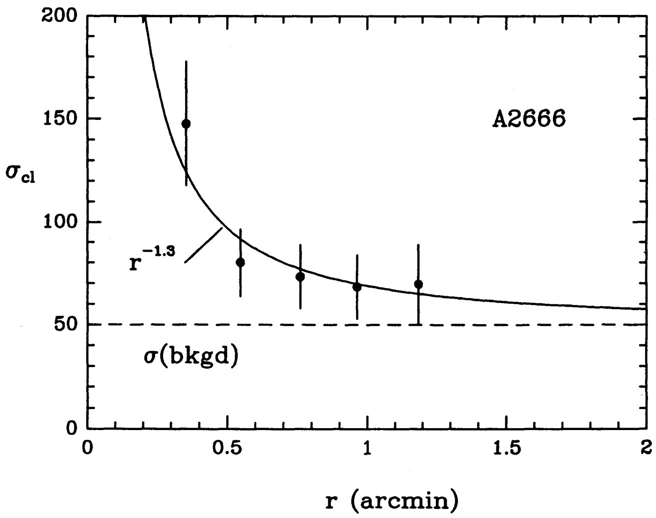

FIG. 2*c*

FIG. 2.—Radial structures of the globular cluster systems around each cD galaxy. Here σ_{cl} is the number of observed starlike images per arcmin^2 in the magnitude range $24 < I < 25$, plotted as a function of radius from galaxy center. The adopted background count level (from the remote background field in the case of A2052 and A2107, and the average of the remote and local estimates from A2666) is plotted as the dashed line in each panel. The best-fitting power law $\sigma \sim r^{-\alpha}$ derived from the data points is drawn in as the solid line.

plotted by location, show a noticeable concentration toward the center of the cD, almost all of them lying within a projected distance of $r \lesssim 40''$ (or about 35 kpc). For this reason, they show up in the residual LF of Figure 1*b* in both the local and remote background solutions at nearly equal amplitude. There are 73 objects in this magnitude range in total. Careful visual inspection of each one of them on the composite frame suggests that one-third (25) are *slightly* nonstellar in appearance (i.e., at a low enough level that they passed through the objective image-classification routine described above), but the remaining two-thirds are clearly starlike and (mostly) uncrowded. If they are indeed dwarf E galaxies, they would have to be extremely compact (diameters $d < 300$ pc). At this stage, we have insufficient information to make any more definite statements about their identity. A more speculative suggestion might be that they represent a small population of more recently formed—and therefore more luminous—globular clusters; if so, they should be distinctly bluer than normal old-globular clusters, and color-index measurement would provide a valuable test.

A2666 (*panel c*)—The residual LF for this galaxy is both the smallest and least secure of our three targets (note the different vertical scale range on Fig. 1*c* compared with the previous two). Since A2666 is at a very different Galactic latitude than our other fields, a large adjustment in the "remote" background level was required, and we suspect that the uncomfortably large residuals at all magnitudes are simply an artifact of an underestimated background. However, for $I > 24$ the two curves agree rather well, and we base our subsequent discussion on the totals for only the "local" background solution.

The radial distributions for the three galaxies are shown in Figure 2. The number of detected starlike images per arcmin^2 for the magnitude range $I > 24$, corrected for incompleteness, is plotted against mean projected radius from galaxy center for several radial zones. Because of the small detected sample sizes and background uncertainties mentioned above, no attempt has been made to model any nonradial (azimuthal) dependence of the spatial distribution. The number density σ is seen to fall off steadily with increasing radius for A2052 and A2107 out to the limits of our image fields, confirming our previous suspicions that we have not surveyed the entire spatial extent of their globular cluster systems. For these two, the plotted background σ_b is that predicted from the remote control field after the small (3%) normalization for Galactic latitude.

For A2666, the results are again much less certain. The plotted σ_b value is an average of the remote and local estimates, and represents only our best present guess at the true background, likely to be uncertain by 30% or more. In fact, only the point for the innermost radial zone stands clearly above background, indicating that the globular cluster system around this galaxy—if indeed we have detected traces of it—is far less populous than in the other two.

With the data as shown, we can make very rough estimates of the central concentrations of the globular cluster systems: modeling the spatial distributions as $\sigma = \sigma_b + kr^\alpha$ and adopting the background values shown in Figure 2, we find (α, k) by simple least squares. The results for the power-law exponent (which is independent of the adopted distance scale H_0) are

$\alpha = -1.39 \pm 0.30$ (A2052), -1.14 ± 0.50 (A2107), and -1.32 ± 0.32 (A2666). These values put them among the most spatially extenced cluster systems known, but are entirely consistent with the established trend for α to become shallower with increasing galaxy luminosity, as do the halos of the underlying galaxies themselves (see Harris 1986, 1993 for further discussion of this point).

4. SPECIFIC FREQUENCIES

The preceding sections demonstrate that the globular cluster systems in our three galaxies, in the shape of their GCLF at the bright end, and in their spatial structure, are within normal limits for giant E galaxies. The next step is to estimate the total cluster population and thus the specific frequency S_N. As with all galaxies at large distances, estimates of S_N are unavoidably rough because we see only the top end of the GCLF. But as noted above, the difference between the high-S_N and low-S_N systems is so large ($S_N \sim 15$ vs. ~ 2) that it is still clearly distinguishable even for galaxies this distant. To estimate S_N, we adopt the approach of comparing the prototype high-S_N system M87 to each of our cD's as directly as possible, rather than simply extrapolating the observed bright end of the GCLF to calculate a total cluster population over all magnitudes. Two versions of this method were tried as follows:

1. The published radial counts and GCLF for M87 (from Harris 1986 and van den Bergh, Pritchet, & Grillmair 1985) were scaled upward in proportion to the luminosity of each galaxy relative to M87, then truncated at the absolute magnitude corresponding to $I(\text{lim}) = 25$ at the distance of each of our three cD program galaxies. We assume here a true Virgo redshift $cz = 1300$ km s^{-1}, and simply take the distance ratio $z(cD)/z(\text{M87})$ to shift the M87 counts to a more remote distance appropriately. Since this procedure uses only *relative* distances, it is independent of H_0. We then compare the number of residual objects we actually observed over our target field with the predicted total we would have observed if the cD had the same specific frequency as M87. (See Butterworth & Harris 1992 for a variant of this method.)

2. We used DAOPHOT/ADDSTAR to add an entire synthesized GCS population to the original frame of each of our three cD's, with the same specific frequency and luminosity function as M87, but with the same radial distribution as the cD galaxy light. This artificial picture—generated by adding in a complete GCLF with anywhere from 10,000 to 17,000 starlike images depending on the galaxy concerned—was then measured in the same way as the original and the residual detected population was compared with that from the real picture.

Both these methods give us a specific frequency *ratio*, denoted $\beta = S_N(cD)/S_N(\text{M87})$ (Butterworth & Harris 1992; McLaughlin et al. 1993). Both procedures have demonstrable advantages, and also disadvantages: the first assumes a radial distribution like the M87 GCS, whereas the second assumes it is like the galaxy light. Nevertheless, both turned out in practice to give highly consistent results. *Assuming* that $S_N(\text{M87}) = 15$ (Harris 1991), we then find $S_N = 22 \pm 7$ for A2052; 13 ± 6 for A2107; and 3 ± 2 for A2666. The result for A2666 might be best regarded as an upper limit because of the difficulty in establishing the true background count level noted above; in any event, NGC 7768 is clearly not a high-S_N galaxy, and may even be subnormal. By contrast, the cD's in A2052 and A2107 appear likely to be high-S_N systems, almost identical within the observational uncertainties to the other known cases: M87, NGC 1399, NGC 3311, and NGC 4874.

5. DISCUSSION

Since the original suggestion by Fabian, Nulsen, & Canizares (1984), considerable interest has attached to the idea that the "excess" populations of clusters in high-S_N cD galaxies might have formed (or be continuously forming) out of the cooling flows from their X-ray halos. Because the amount of mass deposition from the infalling and cooling gas can be $\sim 100\ M_\odot$ yr^{-1} and higher in extreme cases, the supply of gas in cooling-flow galaxies is more than enough to supply the raw material for cluster formation *if* it can condense efficiently into the required $\sim 10^5$–$10^6\ M_\odot$ clumps. The classic difficulties with such an interpretation have been the lack of any direct evidence for "young" globular clusters in the GCS by way of integrated colors or spectral features, and also that the metallicity of the X-ray halo gas (e.g., Rothenflug & Arnaud 1985; Serlemitsos et al. 1993; Forman et al. 1993) is typically 3–10 times higher than the $[\text{Fe/H}] \simeq -1$ characteristic of their halo globular clusters (Fall & Rees 1985; Harris 1991). Other arguments based on the physical state of the gas (e.g., Fabian, Nulsen, & Canizares 1982; Sarazin & O'Connell 1983) and integrated colors (e.g., Schombert, Barsony, & Hanlon 1993, and references cited) also suggest that star formation out of the cooling gas must be heavily weighted to low-mass IMFs. However, renewed interest in the hypothesis has been generated by the discovery of young, massive clusters in the central region of NGC 1275 (Holtzman et al. 1992; Richer et al. 1993), a cD galaxy with a cooling flow rate that is one of the very highest known.

GCS populations have now been surveyed in a total of 12 centrally dominant E or cD galaxies in both rich and poor clusters, most of which also have measurements for X-ray luminosity and cooling flow rates. In Table 1 we summarize the available data for these objects, with column entries as follows:

(1)–(2): Galaxy name and cluster.

(3)–(5): Absolute visual magnitude of the galaxy (assuming $H_0 = 75$), total number of globular clusters, and specific frequency. These data are taken from Harris (1991), Bridges & Hanes (1994), and the present study.

(6)–(7): Temperature of the surrounding X-ray halo gas and its bolometric luminosity. L_X is calculated from the observed emission in the 2–10 keV range and the gas temperature (David et al. 1993). These data are mostly from David et al. (1993), with Fornax from Serlemitsos et al. (1993), and AWM 3 from Kriss, Cioffi, & Canizares (1983).

(8): Cooling flow rate in $M_\odot$ yr^{-1}. These numbers are predominantly from the homogeneous catalog of Arnaud (1988, 1994), with Virgo from Stewart et al. (1984a) and A2107 from Stewart et al. (1984b).

(9): Total mass in hot X-ray gas, from Abramopoulos & Ku (1993) and Jones & Forman (1984), but with Virgo and AWM 4 from Table 3 of David et al. (1990).

(10): Bautz-Morgan class of the galaxy cluster, from Table 14 of McLaughlin et al. (1994a).

Figure 3 is a plot of the total size of the globular cluster population against the strength of the cooling flow, $\dot{M}$. No correlation is evident between these two quantities; nor is there

TABLE 1

Global Parameters for cD Galaxies

Galaxy	Cluster	M_v	N_{glob}	S_N	kT (keV)	L_X^{bol} (10^{43} ergs s^{-1})	$\dot{M}$ ($M_\odot$ yr^{-1})	M_X (10^{13} $M_\odot$)	BM Class
NGC 4486......	Virgo	−22.7	16000	14	2.4	1.85	10	>0.02	III
NGC 1399......	Fornax	−21.2	4800	16	1.1	...	...	...	II–III
NGC 3311......	A1060	−22.4	17000	18	3.9	2.92	4.9	1.5	III
NGC 3842......	A1367	−23.2	19000	10	3.7	7.46	...	4.7	II–III
NGC 4874......	A1656	−23.1	21000	12	8.3	55.5	...	6.5	II
UGC 9799......	A2052	−23.4	46000	20	3.1	16.5	56	1.1	II
UGC 9958......	A2107	−23.4	30000	13	4.2	12.1	8.0	3.2	I
NGC 6166......	A2199	−23.6	10000	4	4.5	28.5	53	5.4	I
NGC 7768......	A2666	−22.9	6000	4	...	...	...	...	I–II
NGC 4073......	MKW 4	−23.1	7200	4	1.7	1.51	9.8	0.1	I
NGC 5424......	MKW 12	−21.6	<2000	<5	...	0.04	...	...	III
NGC 5629......	AWM 3	−21.7	<2000	<5	...	<0.03	...	...	I–II

Notes.—All quantities are tabulated for $H_0 = 75$ km s^{-1} Mpc^{-1}. The L-values are scaled by $(75/H_0)^{-2}$ except for Virgo, which is scaled by $(15/18)^2$, since David et al. 1993 assume $d = 18$ Mpc, and we adopt 15 Mpc. Cooling flow rate $\dot{M}$ is scaled by $(75/H_0)^{-2}$ (see p. 3 of Stewart et al. 1984a), except for Virgo since Stewart et al. 1984b already assume $d = 15$ Mpc. The total X-ray gas mass M_X scales as $H_0^{5/2}$, which can be derived from, e.g., Canizares et al. 1987. For Virgo, we scale M_X from David et al. 1990 by $(21/15)^{-5/2} = 0.43$, since they assume d(Virgo) = 21 Mpc.

any better correlation between $\dot{M}$ and the specific frequency S_N. This conclusion is rendered more obvious by considering individual objects. NGC 6166 (A2199) and UGC 9799 (A2052) differ by almost an order of magnitude in total cluster population, yet possess similar (and high) cooling flow rates. Contrarily, the Coma, Hydra, and Virgo clusters possess quite weak cooling flows yet have among the most populous GCSs known. Unfortunately, we cannot put NGC 1275 itself in Table 1 since nothing quantitative is yet known about its old-halo globular cluster system. However, the addition of one more point regardless of its specific frequency is unlikely to change our conclusions in any major way.

Both quantities ($\dot{M}$, N_{glob}) have significant internal uncertainties. Particularly for the remoter galaxies, N_{glob} may be uncertain by as much as a factor of 2 (cf. the references cited above for the individual cases, and Harris 1991). So are the estimated cooling flow rates (e.g., Arnaud 1988). These large error bars might act to smear out any real correlation; but it seems unlikely to us that a strong intrinsic relation between them could be completely eradicated this way. Our conclusion is therefore that *globular cluster numbers do not depend on the presence or strength of a cooling flow at the present epoch.* Furthermore, observations of galaxy clusters at intermediate redshifts ($z \lesssim 0.4$) indicate that cooling flows are relatively long-lived phenomena that persist for at least several Gyr, and possibly for much of the life of a cluster (e.g., Donahue, Stocke, & Gioia 1992; see also Fabian, Nulsen, & Canizares 1991). If this is correct, then it follows that cooling flows at *any* "recent" epoch (i.e., at any time after the formation of the main body of the galaxy) have never been very relevant to the creation of globular clusters.

The other correlations that can be drawn from Table 1 tend to reinforce this view. In Figures 4 and 5 we show N_{glob} against total X-ray luminosity and total halo gas mass, and in Figure 6 we show specific frequency against the X-ray gas temperature (the latter represents the depth of the intracluster potential well). In all of these plots, the scatter is too large to permit any claim of a global correlation. In summary, we find that neither S_N nor the size of the GCS relate to any evident property of the hot intracluster gas surrounding the cD.

An additional argument against the relevance of cooling flows to globular cluster formation is provided by the velocity dispersion analysis of the clusters in NGC 1399 by Grillmair et al. (1994), and in M87 by Mould, Oke, & Nemec (1987). As

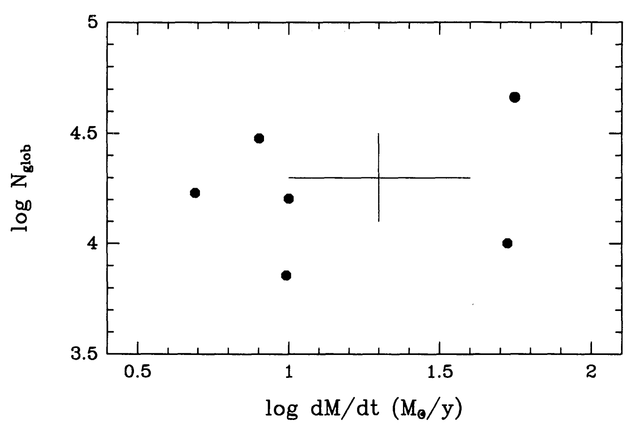

Fig. 3.—Deduced total globular cluster population N_{glob} plotted against cooling flow rate, for the galaxies in Table 1. Here $dM/dt = \dot{M}$ is in units of $M_\odot$ yr^{-1}. A typical error bar for each point is indicated; in general, both quantities are uncertain at the factor-of-two level.

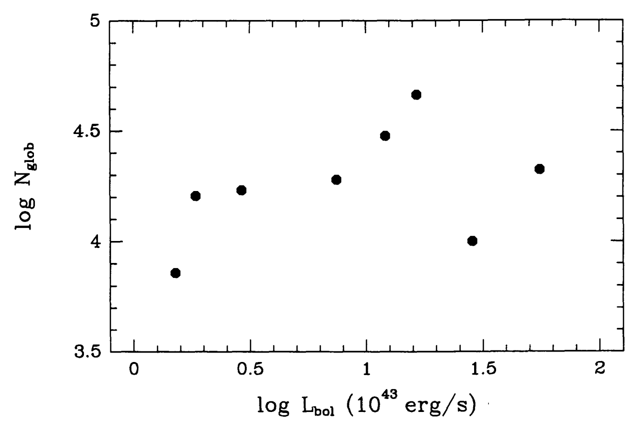

Fig. 4.—Total globular cluster population plotted against total X-ray luminosity from the hot intracluster gas surrounding each cD galaxy, from Table 1.

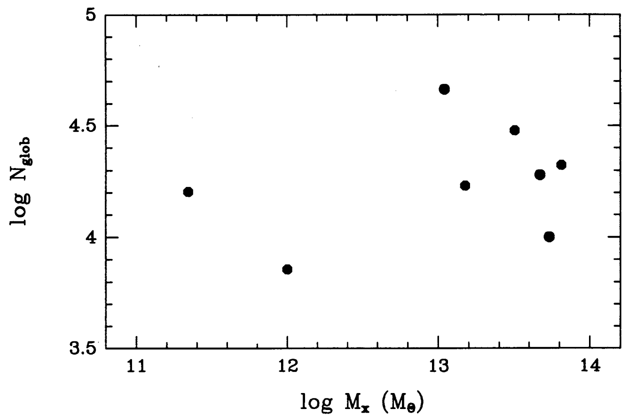

FIG. 5.—Total globular cluster population plotted against total mass M_X in the intracluster gas; from Table 1.

Grillmair et al. discuss, if the majority of the clusters formed out of the inward-flowing gas around NGC 1399 in the potential well of the Fornax Cluster, they should have nearly radial orbits and a very small velocity dispersion. But in both M87 and NGC 1399, the clusters exhibit a *larger* velocity dispersion than the integrated halo light. When this result is added to all the other evidence mentioned above, the case against any significant amount of cluster formation within cooling flows *except* in the centremost parts of these galaxies is now strong. This is the principal conclusion of our study.

Whether or not the presumably large amounts of gas dropping out of the cooling flows can produce massive star clusters in the nuclear regions of these large galaxies is still a matter of debate. NGC 1275, at the center of Abell 426, has one of the largest known cooling flows, at $\dot{M} \sim 100\ M_\odot\ \text{yr}^{-1}$. The dozens of massive globular-like clusters that have recently been discovered (Holtzman et al. 1992; Richer et al. 1983) in its central few kiloparsecs have ages $\sim 10^7$–10^8 yr, on the basis of their integrated colors. Richer et al. (1993) use the observed spread in colors to argue that these clusters may have formed more or less continuously (or else, in a series of frequent but small-scale bursts) over the lifetime of the cooling flow. However, the large random errors in the available photometry, and the presence of significant differential reddening in the center of NGC 1275, suggest to us that any such conclusion is premature. Norgaard-Nielsen et al. (1993) argue in favor of cluster formation out of the cooling flow, but in a somewhat different way: they suggest that a cooling catastrophe has developed and thus that a single prominent burst of formation took place $\sim 10^8$ yr ago. Still another alternative, favored by Holtzman et al. (1992), is that the cluster formation resulted not from the cooling flow but from a sudden merger event (out of neutral gas obtained from the accretion of a disk galaxy; the high-velocity H I system also accompanying NGC 1275 shows that it is interacting quite strongly with its neighboring galaxies and thus can accumulate a fresh supply of gas in quite a different way than the cooling flow provides). Perhaps the strongest argument that these young, inner clusters are *not* products of the cooling flow is one summarized by Zepf & Ashman (1993): namely, that other galaxies in which similar star-forming activity has taken place, such as NGC 3597, 5128, 5173, and 7252, do not have strong cooling flows. They have, however, clearly undergone recent accretions or mergers (see Lutz 1991; Whitmore et al. 1993; Zepf & Ashman 1993).

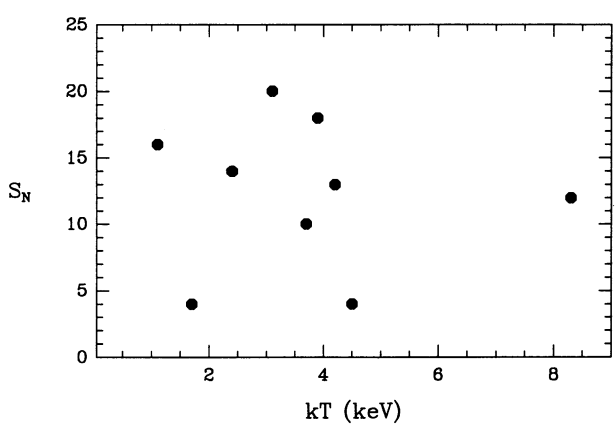

FIG. 6.—Specific frequency S_N of the globular cluster system plotted against the X-ray gas temperature T (in keV).

In short, several large galaxies now show evidence of recent mergers or infall which have led to the relatively sudden central accumulation of large amounts of neutral gas. No matter how this gas is assembled, when compressed to high density it yields just the right conditions for the formation of massive star clusters (see the discussions of Ashman & Zepf 1992; Richer et al. 1993; West 1993). A specific physical model for this process, by which clusters of the right characteristic size and mass form out of dense protocluster cores embedded in supergiant molecular clouds, has been developed by Harris & Pudritz (1994).

Can the formation of clusters in these active galaxies affect the correlations shown in Figures 3–6? Some authors (e.g., Schweizer 1987; Lutz 1991; Holtzman et al. 1992) claim that the process of merger-stimulated cluster formation will increase the global value of S_N summed over the entire galaxy, thus removing one objection to the hypothesis that large E galaxies formed from merging disk systems, and (possibly) providing a source for the high-S_N cD's. But this claim is, in general, not true. The reason is that the merger-stimulated star formation produces *both* clusters and field stars, and the *ratio* of these two modes is what determines the specific frequency. Thus S_N may increase, stay the same, or even *decrease* as a result of a merger, depending on the efficiency of cluster formation relative to field-star formation. The nature of the problem is correctly stated by Ashman & Zepf (1992), but seems not to be commonly realized. Zepf & Ashman (1993) summarize the available data for these galaxies, and find that the typical cluster formation efficiency (defined as M_{cl}/M_g, where M_g is the mass of gas available for star formation and M_{cl} is the mass that ends up in bound star clusters) is at the "normal" level of $\sim 1\%$ that characterizes cluster formation in contemporary giant molecular clouds, and which also seems to have applied to the early galaxy formation epoch in general (Harris & Pudritz 1994). For this reason, we expect that S_N will remain roughly invariant even through merger-induced cluster formation, and even if the recent cluster formation extends well out into the halo of the merged galaxy, as Whitmore et al. (1993) show is the case for NGC 7252.

It also seems unlikely to us that these recently formed cluster populations can have any large-scale effects on the correlations described above, on the simple basis of total cluster population size. The absolute numbers of globular-like clusters forming now in the centers of such galaxies are rather small (even in the extreme cases of NGC 1275 and NGC 7252, there are at most ~ 50 clusters more massive than $\sim 2 \times 10^5\ M_\odot$ and within 10 kpc of the nucleus). Although the spatial distribution of young clusters matches that of the underlying galaxy light reasonably well in these systems (see particularly Fig. 15 of Whitmore et al. 1993), they would add negligibly to the total of old-halo globular clusters already present in a typical high-S_N galaxy (this will be especially true after the effects of dynamical friction, tidal shocking, etc., have a change to remove the young clusters in the innermost regions, where they appear to be forming in the largest numbers). If the overall cluster formation efficiency remains anywhere near 1% (see above), then the only epoch at which the huge M87-like cluster populations can have been built in is during the protogalactic era itself, when the galaxies were almost entirely gaseous (Ashman & Zepf 1992).

For a final correlation to be discussed in this section, we show in Figure 7 the specific frequency against Bautz-Morgan class, that is, the relative dominance of the central elliptical or cD. We verify the conclusion of McLaughlin et al. (1993, 1994) that high-S_N cD's tend to be found only in BM classes II–III (that is, in clusters where they are *not* extremely dominant); but once again the global correlation is not strong. Note that two galaxies (those in AWM 3 and MKW 12; see Bridges & Hanes 1994) are plotted only as upper limits. These latter sparse systems are in very different environments from the rich Abell-type clusters for which the Bautz-Morgan classification scheme was originally defined, and it is not entirely clear whether they should be directly compared to the Abell objects in this way. Even so, they are consistent with the correlation defined by the Abell-cluster cD's. We emphasize here only that no high-S_N galaxy has ever been found in a sparse cluster, that is, that the total richness of the galaxy environment still seems to be a necessary, but not sufficient, condition for high specific frequency.

In our opinion, the overall impression from Figures 3–7 is that we are looking at a rather inhomogeneous set of galaxies which have undergone a wide variety of individual histories. We can imagine that most of them (perhaps all the cD's in the Abell-type clusters) may have undergone an initial high-efficiency burst of globular cluster formation during the protogalactic phase, depending on the depth of their initial potential well and the ambient gas density (see West 1993; Harris & Pudritz 1994) and therefore begun with higher than average S_N. In particular, M87 itself seems to have accumulated its cD envelope at about the same early epoch. The reason is that the cD envelope by itself has a high S_N like the central body of M87, and this could not have resulted from later accretion of other fully formed galaxies, which all have low S_N (see McLaughlin et al. 1993). However, each of the cD's in their own surrounding Abell clusters may later have undergone individually very different series of mergers and accretions of other galaxies, building up in size to the objects we now see. During any such process involving the accretion of already formed galaxies, S_N is likely to decrease substantially in a global sense, or at best stay roughly constant, since other galaxies merging with them will almost invariably have lower S_N. For clusters of BM type I, the resulting cD became especially dominant, thus should have been most susceptible to this GCS dilution effect. The expected effect should therefore work in the correct direction with BM type to produce the rough correlation that we now see in Figure 7, but correctly reconstructing these individual histories will be a formidable task.

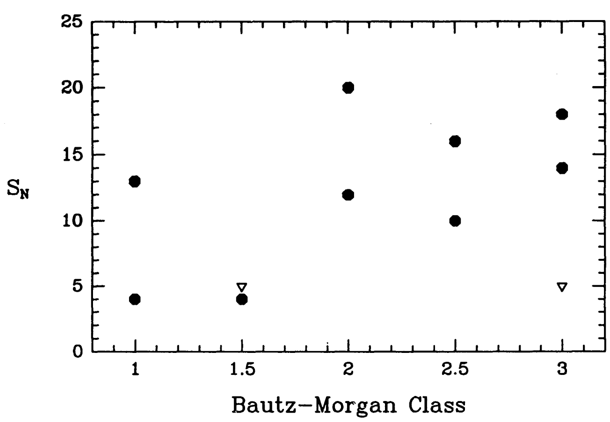

FIG. 7.—Specific frequency S_N of each cD galaxy in Table 1, plotted against the Bautz-Morgan type of the surrounding cluster of galaxies. Open triangles at the bottom of the graph represent upper limits on the estimated specific frequency ($S_N < 5$; see Table 1). BM class I galaxies are more centrally dominant within their clusters, BM class III are less dominant. The weak correlation first noted by McLaughlin et al. (1993) for S_N to be higher for cD's that are *less* dominant in their environments is shown graphically here. Note that the two points denoted as upper limits (*open symbols*) are galaxies in sparse (non-Abell) clusters, and thus are not strictly comparable to the others in the list. See § 5 for additional discussion.

As has already been hinted, the main exception to the scenario we have just outlined would be to have mergers taking place at such an early epoch that the colliding objects were still mostly, or entirely, gaseous. Globular clusters could then form in significant numbers throughout the main body and halo of the merger and not just in the central few kiloparsecs. However, what we are describing in this case is no longer a merger or accretion in the currently observed sense of the word (NGC 1275, 3597, 7252, and others; see above) but the primary galaxy formation epoch itself (Harris 1986, 1991; Ashman & Zepf 1992).

6. SUMMARY

1. We have obtained deep, high-resolution imaging for the central cD galaxies in three Abell clusters (A2052, A2107, A2666) which reveal globular cluster systems in each case. The shape of the bright end of the GCLF, and the spatial distribution of the globular cluster system, are just as expected for a normal globular cluster population such as we find in the nearby Virgo ellipticals.

2. Our estimates of the total halo cluster populations in each galaxy suggest that the cD's in A2052 and A2107 are clearly high-S_N systems like M87, whereas the cD in A2666 has only a normal or subnormal GCS.

3. For a combined total of 12 centrally dominant cD galaxies in a wide variety of galaxy clusters, we find that neither the total number of globular clusters nor the specific frequency correlate in any way with the presence of X-ray intracluster gas (cooling flow rate, gas temperature, total gas mass, or other parameters). We use these data to argue that contemporary cooling flows—and in a broader sense, the existence of hot intracluster gas—are not causally connected to globular cluster formation in any important way. A rough correlation does exist between Bautz-Morgan type and S_N, as first stated by McLaughlin et al. (1993), in the sense that *more* centrally dominant cD's are *less* likely to have populous globular cluster systems.

We interpret this combination of results in a rather traditional way, namely, that the main epoch of globular cluster formation in these very large galaxies belonged to the protogalactic era, well before the present-day X-ray halos or cooling flows had been set up. Since at best ~1% of the star-forming mass gives rise to gravitationally bound globular clusters (e.g., Richer et al. 1993; Zepf & Ashman 1993; Harris & Pudritz 1994), it appears to us that the very large numbers of massive clusters we find in M87 and galaxies like it must have formed during a phase when there was the largest possible amount of dense, cool gas available—in short, the galaxy formation epoch.

Measuring the globular cluster populations in additional giant E and cD galaxies would be of great value. By increasing the sample size further, we can cover the true range of galaxy sizes, environments, and evolutionary stages much more thoroughly than we have been able to do so far; many other targets are available in the redshift range $cz \sim 5000$–20,000 km s^{-1}. However, the most efficient way to attack such a program observationally may now be by using surface brightness fluctuations (Wing et al. 1995). For a remote giant elliptical, the galaxy light itself becomes a virtually smooth luminous surface, and the SBF amplitude instead is dominated by the globular cluster population. The method has been applied successfully to deriving the S_N profile in M87 (Wing et al.) and may be effective at considerably larger distances.

Note added in manuscript.—In a recent dynamical modeling study, Bassino, Muzzio, & Rabolli (1994, ApJ, 431, 634) have followed the dynamical evolution of dwarf elliptical-like satellites orbiting in the potential field of a large central cD-like galaxy. They find that *nucleated* dE's can survive over long periods of time even if their orbital pericenters pass quite close to the central cD (50 kpc or less); by contrast, nonnucleated dwarfs are too diffuse to survive at similar pericenters, tending to suffer complete tidal disruption. Interestingly, these authors find that after several orbits the nucleated dE's are cut back from initial sizes of $r_t \sim 2$ kpc down to typically 200 pc or less. The diameters, luminosities, and radial locations of these truncated dE's therefore correspond fairly closely to the small population of bright, compact objects that we find around A2107. The original goal of the experiments by Bassino et al. was to see if the nuclei of these "cannibalized" dE,N satellites might become globular clusters after the surrounding envelope of the dE had been completely stripped away. We are skeptical that this mechanism can be an important source of accreted globular clusters, because the simulations of Bassino et al. already indicate that particular result would happen only rarely. Instead, it seems much more plausible that this mechanism will take an initial population of a few dozen or hundred dwarf satellites and leave behind a smaller number of unusually compact dE remnants. However, if this is indeed what we are seeing around A2107, it is puzzling that we do not also see it around A2052 or other, similar, environments.

We thank Keith Arnaud for transmitting his data for cooling flow rates to us, and Steve Zepf for a critical reading of the manuscript. Financial support through the Natural Sciences and Engineering Research Council of Canada and the National Research Council is gratefully acknowledged.

REFERENCES

Abramopoulos, F., & Ku, W. H.-M. 1983, ApJ, 271, 446
Arnaud, K. 1988, in Cooling Flows in Clusters and Galaxies, ed. A Fabian (Dordrecht: Kluwer), 31
———. 1994, private communication.
Ashman, K. M., & Zepf, S. E. 1992, ApJ, 384, 50
Bassino, L. P., Muzzio, J. C., & Rabolli, M. 1994, ApJ, 431, 634
Bridges, T. J., & Hanes, D. A. 1994, ApJ, 431, 625
Bridges, T. J., Hanes, D. A., & Harris, W. E. 1991, AJ, 101, 469
Butterworth, S. T., & Harris, W. E. 1992, AJ, 103, 1828
Canizares, C. R., Fabbiano, G., & Trinchieri, G. 1987, ApJ, 312, 503
Christian, C. A., Adams, M., Barnes, J. V., Butcher, H., Hayes, D. S., Mould, J. R., & Siegel, M. 1985, PASP, 97, 363
David, L. P., Arnaud, K. A., Forman, W., & Jones, C. 1990, ApJ, 356, 32
David, L. P., Slyz, A., Jones, C., Forman, W., Vrtilek, S. D., & Arnaud, K. A. 1993, ApJ, 412, 479
Donahue, M., Stocke, J. T., & Gioia, I. M. 1992, ApJ, 385, 49
Fabian, A. C., Nulsen, P. E. J., & Canizares, C. R. 1982, MNRAS, 201, 933
———. 1984, Nature, 310, 733
———. 1991, Astron. Ap. Rev., 2, 191
Fall, S. M., & Rees, M. J. 1985, ApJ, 298, 18
Fischer, P., Hesser, J. E., Harris, H. C., & Bothun, G. D. 1990, PASP, 102, 5
Forman, W., Jones, C., David, L., Franz, M., Makishima, K., & Ohashi, T. 1993, ApJ, 418, L55
Grillmair, C. J., Freeman, K. C., Bicknell, G. V., Carter, D., Couch, W. J., Sommer-Larsen, J., & Taylor, K. 1994, ApJ, 422, L9
Harris, W. E. 1986, AJ, 91, 822
———. 1987, ApJ, 315, L29
———. 1991, ARA&A, 29, 543
———. 1993, in The Globular Cluster—Galaxy Connection, ed. G. H. Smith & J. P. Brodie (ASP Conf. Ser. 48), 472
Harris, W. E., Allwright, J. W. B., Pritchet, C. J., & van den Bergh, S. 1991, ApJS, 76, 115
Harris, W. E., Pritchet, C. J., & McClure, R. D. 1993, in The Globular Cluster—Galaxy Connection, ed. G. H. Smith & J. P. Brodie (ASP Conf. Ser. 48), 572
Harris, W. E., & Pudritz, R. E. 1994, ApJ, 429, 177
Harris, W. E., Smith, M. G., & Myra, E. S. 1983, ApJ, 272, 456
Harris, W. E., & van den Bergh, S. 1981, AJ, 86, 1627
Heckman, T. M., Baum, S. A., van Breugel, W. J. M., & McCarthy, P. 1989, ApJ, 338, 48
Holtzman, J. A., et al. 1992, AJ, 103, 691
Jones, C., & Forman, W. 1984, ApJ, 276, 38
Kriss, G. A., Cioffi, F. F., & Canizares, C. R. 1983, ApJ, 272, 439
Landolt, A. U. 1983, AJ, 88, 439
Lutz, D. 1991, A&A, 245, 31
Malumuth, E. M., & Kirshner, R. P. 1985, ApJ, 291, 8
McClure, R. D., et al. 1989, PASP, 101, 1156
McLaughlin, D. E., Harris, W. E., & Hanes, D. A. 1993, ApJ, 409, L45
———. 1994, ApJ, 422, 486
McLaughlin, D. E., Secker, J., Geisler, D., & Harris, W. E. 1995, AJ, in press
Mould, J. R., Oke, J. B., & Nemec, J. M. 1987, AJ, 93, 53
Norgaard-Nielsen, H. U., Goudfrooij, P., Jorgensen, H. E., & Hansen, L. 1993, A&A, 279, 61
Pritchet, C. J., & Harris, W. E. 1990, ApJ, 355, 410
Richer, H. B., Crabtree, D. R., Fabian, A. C., & Lin, D. N. C. 1983, AJ, 105, 877
Rothenflug, R., & Arnaud, M. 1985, A&A, 144, 431
Sarazin, C. L., & O'Connell, R. W. 1983, ApJ, 268, 552
Schombert, J. M., Barsony, M., & Hanlon, P. C. 1993, ApJ, 416, L61
Schweizer, F. 1987, in Nearly Normal Galaxies: From the Planck Time to the Present, ed. S. M. Faber (New York: Springer), 18
Serlemitsos, P. J., Loewenstein, M., Mushotzky, R. F., Marshall, F. E., & Petre, R. 1993, ApJ, 413, 518
Stetson, P. B. 1987, PASP, 99, 191
Stewart, G. C., Canizares, C. R., Fabian, A. C., & Nulsen, P. E. J. 1984a, ApJ, 278, 536
Stewart, G. C., Fabian, A. C., Jones, C., & Forman, W. 1984b, ApJ, 285, 1
Thompson, L. A., & Valdes, F. 1987, ApJ, 315, L35
van den Bergh, S., Pritchet, C. J., & Grillmair, C. J. 1985, AJ, 90, 595
West, M. J. 1993, MNRAS, 265, 755
Whitmore, B., Schweizer, F., Leitherer, C., Borne, K., & Robert, C. 1993, AJ, 106, 1354
Wing, D., Harris, G. L. H., Hanes, D. A., & Harris, W. E. 1995, ApJ, in press
Zepf, S. E., & Ashman, K. M. 1993, MNRAS, 264, 611