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GLOBULAR CLUSTER SYSTEMS ASSOCIATED WITH cD GALAXIES IN POOR CLUSTERS

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ABSTRACT

We present an analysis of direct CCD images of the central cD galaxies of four poor clusters (Albert, White, & Morgan 1977; Morgan, Kayser, & White 1975) obtained at the prime focus of the Canada-France-Hawaii Telescope. A globular cluster system (GCS) is detected in only one of the galaxies: NGC 4073 (MKW 4); it has a specific frequency of $S_N \simeq 4 \pm 4$, a value typical for an "average" elliptical of no particular distinction (Harris 1991). In the other three clusters, upper limits of $S_N < 5$–10 can be set on the specific frequency of any attendant GCS. These findings strongly suggest that mergers are *not* important in the generation of extremely populous GCSs, since the central galaxies in poor clusters presumably have more active merging histories than do their counterparts in richer surroundings. It is noted that MKW 4 has a moderate cooling flow, which may play some role in the formation of its GCS; the other poor clusters studied have neither the cooling flow nor the detected GCS. Finally, we note that the GCS associated with NGC 4073, the cD galaxy in MKW 4, is among the *least* centrally concentrated of any studied to date. This supports a suggestion by Harris (1991) that the degree of central concentration of a GCS is a function of the luminosity of the parent galaxy, with the most luminous galaxies having the most distended cluster systems.

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

1. INTRODUCTION

Globular cluster systems (hereafter GCSs) have now been studied in some dozens of galaxies in a variety of environments, a large enough database that we may be able to address questions of astrophysical significance with reasonable expectations of formulating plausible first-order answers (see Harris 1991 for a recent thorough review). Perhaps the outstanding question for many years has been that of the origin of the superabundant globular cluster populations surrounding some, but apparently not all, of the centrally placed elliptical galaxies in rich clusters (Harris & Smith 1976; Harris, Smith, & Myra 1983; Hanes & Harris 1986a, 1986b; Harris 1987; Thompson & Valdes 1987; Bridges, Hanes, & Harris 1991; Pritchet & Harris 1990). As is now customary, we express the luminosity-normalized globular cluster content of a galaxy in terms of its specific frequency S_N (Harris & van den Bergh 1981) and note, by way of example, that in this respect a galaxy such as M87 in the Virgo cluster is about 3 times overabundant in globular clusters relative to similar galaxies in less privileged locations.

Early explanations (Muzzio 1987, 1988) in terms of galaxy mergers, with a central galaxy accreting or stripping globular clusters from its neighbors, seemed to be ruled out (van den Bergh 1990) on the grounds that mergers and stripping should lead to the accretion of stars and clusters indifferently, with no consequent increase in the globular cluster specific frequency. Recent theoretical work, however, has led to a reconsideration of this process: Ashman & Zepf (1992) in particular have argued that mergers at a suitably early epoch could lead very naturally to a superabundant globular cluster population if the merger fragments were gaseous at that time and if the mergers sparked vigorous cluster formation (with clusters being formed preferentially over field stars if S_N is to increase as a result). In a further elaboration of this picture, Zepf & Ashman (1993) were able plausibly to explain certain other observed attributes of the resultant GCS—in particular, color gradients within the GCS, bimodal color distributions, and the distended nature of the system relative to the more centrally concentrated galaxian light, features seen in many of the superabundant systems (Harris 1991).

Ashman & Zepf's (1992) timely work, motivated in part by the apparent discovery of young clusters in the merging galaxy NGC 3597 (Lutz 1991), received additional observational support almost immediately in Holtzmann et al.'s (1992) serendipitious discovery, in *Hubble Space Telescope* (*HST*) WF/PC images, of a number of apparently young proto–globular clusters in NGC 1275, a galaxy which may also have undergone a recent merger/accretion. The situation is confused, however, by the greater complexity of NGC 1275, including the presence of a strong cooling flow (Fabian et al. 1981). But on the positive side, the earlier case of NGC 3597 seems more clear-cut, and recent WF/PC observations of NGC 7252 (Whitmore et al. 1993) and subsequent ground-based spectroscopy (e.g., Schweizer & Seitzer 1993) strongly suggest the presence of young clusters in that galaxy as well, so the general scenario seems promising. We shall discuss these matters further in § 4 in the light of our findings.

If mergers are important in the building up of superabundant GCSs, then it would seem natural that cD galaxies in poor clusters should exhibit the effect well: in such clusters, the galaxy-galaxy velocities are low, so mergers should happen especially frequently (see § 2.1 below). The present paper describes a study designed to elucidate this point. Our motivation in undertaking the observations described herein was to address the following fundamental questions: Is the central dominance of a galaxy in a cluster by itself sufficient to guarantee it a superfluity of globular clusters, or is there a demonstrable dependence upon the larger galactic environ-

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ment; and, if so, what role does the dynamical history play? As we shall demonstrate, the attributes of the poor clusters chosen for study allowed us to address a corollary question: Is there any dependence of GCS specific frequency upon the presence and amplitude of a cooling flow?

This paper will take the following form: in § 2, we discuss the properties of the poor clusters and relate some of the earlier relevant astronomical scrutiny they have received. In § 3, we describe the particular clusters chosen for the present study, and we present details of the observing and data reduction strategy. The resultant data are presented and interpreted in § 4, especially in the context of cDs as merger products, while in § 5 we summarize our principal scientific conclusions.

2. POOR CLUSTERS OF GALAXIES

2.1. *Optical Studies*

Using the Palomar Observatory Sky Survey, Morgan, Kayser, & White (1975; hereafter MKW) and Albert, White, & Morgan (1977; hereafter AWM) identified 23 potential poor clusters of galaxies. As redshifts became available it was determined that the MKW/AWM objects are indeed real physical clusters or groups (Thomas & Batchelor 1978; Stauffer & Spinrad 1980; Hintzen 1980; Beers et al. 1984; Malumuth & Kriss 1986). Price et al. (1991) have shown that the MKW clusters are representative of poor clusters in terms of X-ray luminosities, Rood-Sastry types (Rood & Sastry 1971), velocity dispersions, and the contrast between the first- and second-brightest galaxies. Thus, our use of the phrase "poor clusters" in the following discussion may be taken to mean the MKW/AWM sample, unless otherwise indicated. Most poor clusters contain a very luminous, central dominant galaxy (which we will call a "cD" galaxy, although, as described below, there are some differences between these and the more familiar rich cluster cDs) which invariably lies at the kinematic center of the cluster (e.g., Hintzen 1980; Stauffer & Spinrad 1980; Quintana & Lawrie 1982; Beers et al. 1984; Malumuth & Kriss 1986). This last finding is confirmed by X-ray studies (see below). Recent work (Beers et al. 1993) shows that $\sim\frac{2}{3}$ of the cD galaxies in the MKW/AWM sample have velocities consistent with that of their cluster means.

The projected cluster velocity dispersion, σ_{cl}, is typically a factor of 2 lower for poor clusters then for rich clusters (Beers et al. 1984; Malumuth & Kriss 1986; Price et al. 1991; Struble & Rood 1991; Beers et al. 1993). Indeed, these values of σ_{cl} are comparable to the internal velocity dispersions of the cD galaxies themselves (Malumuth & Kirshner 1985), which supports a merger origin for poor cluster cDs. The available surface photometry (Thuan & Romanishin 1981; Morbey & Morris 1983; Malumuth & Kirshner 1985) shows that poor cluster cDs are more diffuse and brighter in their central regions than their rich cluster counterparts. Finally, the poor cluster cDs lack the luminous extended envelopes seen in rich cluster cDs (Thuan & Romanishin 1981). These observations suggest that dynamical friction and galactic cannibalism are more important in poor clusters, while tidal stripping is more important in rich clusters. Such differences are also expected on "theoretical grounds" (e.g., Binney & Tremaine 1987), given the lower velocity dispersions of the poor clusters.

2.2. *X-Ray Data and Cooling Flows*

Poor clusters are commonly X-ray sources with luminosities $\sim 10^{42}$–10^{43} ergs s^{-1}, lower than for rich clusters (where $L \sim 10^{43}$–10^{45} ergs s^{-1}). Kriss, Cioffi, & Canizares (1983) detected X-ray emission in 12 of 16 MKW/AWM clusters observed with *Einstein*. In all 12 detected clusters, the X-ray emission is centered on the dominant galaxy. A similar result is found for other poor clusters (Burns, White, & Haynes 1981; Price et al. 1991) and suggests that poor cluster cDs are located in the dynamical centers of their clusters. For the six brightest galaxies, Kriss, Cioffi, & Canizares (1983) found that the X-ray emission is quite smooth, symmetrical, and fairly extended (out to $\sim$1 Mpc). They derived the central densities of the ICM, the binding masses, and the M/L ratios of these six clusters, and found these properties to be on the low end of the range of values found for rich clusters (see also Malumuth & Kriss 1986; Price et al. 1991).

Kriss, Cioffi, & Canizares (1983) and Canizares, Stewart, & Fabian (1983) found that the cooling time t_{cool} is less than the Hubble time, t_H, for four of the MKW/AWM poor clusters (MKW 4, MKW 3S, AWM 7, and AWM 4). The finding that $t_{cool} < t_H$, together with the centrally peaked central surface brightness distributions, suggests strongly that the X-ray emitting gas forms a cooling accretion flow onto the cD galaxy in these clusters. The inferred mass accretion rates for these four clusters are in the range 20–100 $M_\odot$ yr^{-1} (Canizares, Stewart, & Fabian 1983; Malumuth & Kriss 1986). Cooling flows are also observed in a large fraction of rich clusters, with an inflow rate of typically 100 $M_\odot$ yr^{-1}.

2.3. *Dynamical Considerations and Summary*

The balance of the evidence shows that poor and rich clusters present much different dynamical environments. Poor clusters represent a smooth continuation from the rich Abell clusters to lower richness systems in terms of kinematics/dynamics and X-ray properties. If GCS properties are dependent on the large-scale (galaxy) cluster environment, then one would expect to see differences between the GCSs of galaxies found in rich and in poor clusters. However, we are not aware of any previous studies of the GCSs of poor cluster galaxies.

3. GLOBULAR SYSTEMS OF POOR CLUSTER cDs

3.1. *Our Sample: Four Poor Clusters*

In an attempt to answer some of the important questions posed above, we acquired V CCD frames of the cD galaxies in MKW 4 (NGC 4073), MKW 12 (NGC 5424), AWM 2 (NGC 4213), and AWM 3 (NGC 5629) in 1990 May at the Canada-France-Hawaii Telescope (CFHT). In Table 1, we list the relevant attributes of the cD galaxies and their (galaxy) clusters. These four galaxies were chosen from the MKW/AWM sample partly on the basis of their relatively low recession velocities, in order to make practicable the detection of a "normal" (i.e., Virgo-like) GCS under typical observing conditions at the CFHT. We were especially motivated to include one cluster, MKW 4, which is a bright X-ray source with a cooling flow ($\dot{M} \simeq 20\ M_\odot$ yr^{-1}; Canizares, Stewart, & Fabian 1983). The remaining three clusters are less X-ray bright than MKW 4, and none of the three has an inferred cooling flow. There is some confusion about AWM 3—it was detected by Price et al. (1991) but not by Kriss, Cioffi, & Canizares (1983) using the same *Einstein* data; it is a marginal detection in any case. None of the poor clusters is as globally rich as Virgo, Fornax, or Coma, yet all of the poor cluster cDs in our sample are at least as luminous as M87. Therefore, our sample of four poor cluster cDs permits at least a rudimentary test of ideas of globular formation involving cluster environment and cooling flows.

TABLE 1

OBSERVATIONAL PROPERTIES OF POOR CLUSTER cDs

Cluster (1)	cD (NGC) (2)	l (3)	b (4)	V_{cl}[a] (km s^{-1}) (5)	$\Delta(V_{cD} - V_{cl})$[a] (km s^{-1}) (6)	σ_{cl}[a] (km s^{-1}) (7)	M_V^T (8)	L_x (9)	Cooling flow? (10)
MKW 4	4073	276.9	62.4	6098	−141	537	−23.1	19.1	Yes[b]
MKW 12	5424	349.9	65.5	6182	−164	902	−21.6	1.89	No
AWM 2	4213	232.3	81.3	6720	−21	289	−22.3	...	...
AWM 3	5629	35.1	68.3	4477	17	287	−21.7	1.32	No

NOTE.—Cols. (1) and (2) identify the cluster and cD galaxy; cols. (3) and (4) give the galactic longitude and latitude of the cD galaxy; col. (5) gives the cluster recession velocity; col. (6) gives the velocity difference between the cD galaxy and the cluster; col. (7) gives the cluster velocity dispersion; col. (8) gives the absolute V magnitude of the cD galaxy (calculated using V_{gal} and assuming $H_0 = 75$ km s^{-1} Mpc^{-1}); col. (9) gives the cluster X-ray luminosity (in units of 10^{42} ergs s^{-1} from Price et al. 1991); and col. (10) indicates whether a cluster cooling flow has been detected.

[a] All velocity data are taken from Beers et al. 1993.

[b] $\dot{M} \simeq 20\ M_\odot$ yr^{-1} (Canizares et al. 1983).

3.2. *Details of the Observations*

The data were obtained during two observing runs spread over four nights in late 1990 May at the CFHT, using the RCA 4 CCD at prime focus (at which location the image scale of 0".22 pixel^{-1} and CCD size of 640 × 1024 pixel yields a field of 2'.35 × 3'.76). For NGC 4073, NGC 4213, and NGC 5629, we obtained several 1200 s V exposures with the galaxy centrally located on the chip, and comparable exposures of background fields well offset from the galaxy so that the background contamination could be determined. For NGC 5424, we placed the galaxy on one edge of the chip, but did not acquire a separate background field. We also acquired brief exposures of several standard star fields during each night. The seeing was generally good (FWHM 0".6–1".0). All three nights of the second run appeared to be photometric, but there is some question about whether night 1 of the first run (when the NGC 5629 program frames were taken) was photometric. Table 2 contains a summary of the observations.

3.3. *Data Analysis*

The data were preprocessed (bias-subtracted, dome flat-fielded, and trimmed) at CFHT using the IRAF CCDPROC package. All subsequent analysis was done using the DAOPHOT package and other IRAF routines on a SPARC workstation at our home institution, following closely our now-routine procedures (see, e.g., the detailed discussion in Bridges & Hanes 1992). There were two small amendments to our previous procedures:

1. To correct the obvious fringing in our V frames, we constructed a dark-sky flat field using "dithered" observations of the background field associated with NGC 4073; that is, successive 1200 s exposures of this field were shifted by ~10" steps. A median of the shifted frames leaves only the fixed-pattern fringing and a few individual bad pixels.

2. Unlike the case of M104, we did not have to worry about the exclusion of a disk for any of these elliptical cDs. After the "Fischer procedure" (Fischer et al. 1990; see the discussion in Bridges & Hanes 1992) is finished, we were able safely to perform photometry outside a circular region ~20" from the galaxy center. Figure 1 shows a representative final, co-added, median-filtered image for NGC 4073. (Note the close companion to NGC 4073, as noted by van den Bergh 1975.)

We carried out aperture photometry on our standard stars in the usual fashion. Least-squares solutions were obtained for

TABLE 2

OBSERVING RECORD

Field	Exposure (s)	FWHM	X
NGC 4073 Galaxy	8400	0".85	1.30
NGC 4073 Background	7200	0.85	1.40
NGC 5424 Galaxy	4800	0.85	1.40
NGC 4213 Galaxy	6000	0.70	1.10
NGC 4213 Background	4800	0.90	1.40
NGC 5629 Galaxy	6000	0.85	1.25
NGC 5629 Background	6000	0.80	1.35

NOTE.—A separate background field was not acquired for NGC 5424.

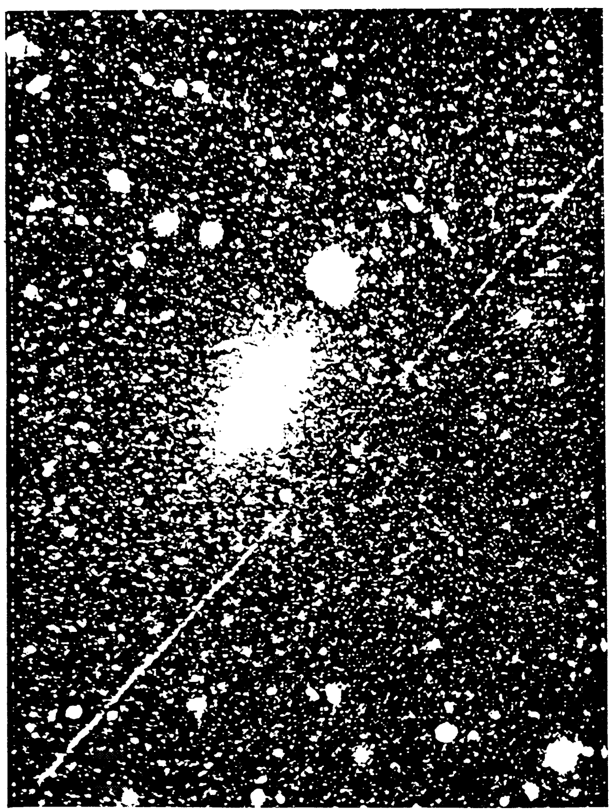

FIG. 1.—NGC 4073 (MKW 4) in a co-added, median-filtered image. Note the close companion.

the standards in each of the three nights of the second run separately, and then with data from all three nights added together. For the first run, nonphotometric conditions meant that no standards were obtained on night 2, and instead data from nights 1 and 3 have been added together. We performed three iterations for each solution, rejecting stars more than 3 σ from the mean in each pass; convergence was always reached in three iterations or fewer. No significant night-to-night variations were seen in the transformation coefficients for either run and the rms scatter was $\sim$0.02 mag. The final transformation coefficients for each run are

$$\text{Run 1:}\quad (v - V) = 0.589 + 0.122X + 0.051(B-V)\,, \quad 142 \text{ objects}\,, \tag{1}$$

$$\text{Run 2:}\quad (v - V) = 0.551 + 0.134X + 0.039(B-V)\,, \quad 95 \text{ objects}\,. \tag{2}$$

In equations (1) and (2), the instrumental magnitude is defined as $v = 25.00 - 2.5 \log N$, where N is the number of ADUs corresponding to an exposure time of 1 s. We see that there is good agreement in the transformation coefficients between the two runs.

The usual DAOPHOT/ADDSTAR experiments (e.g., Bridges & Hanes 1992) were performed to determine the photometric completeness and uncertainties. The limiting magnitudes (defined to be the magnitude corresponding to a completeness level of 50%) for our fields range over $V_{\rm lim}$ = 24.0–25.0, while the corresponding random and systematic photometric uncertainties at these limiting magnitudes are $\sim$0.20 and $\sim$0.05 mag, respectively.

3.4. *Results for MKW 4*

3.4.1. *The Radial Surface Density Profile*

For NGC 4073, a visual inspection reveals an evident central concentration of globular cluster candidates—i.e., all objects from the last ALLSTAR run which were subsequently classified as stellar on the galaxy image, down to $V = 25.0$ (the 50% completeness level).

To quantify this finding, we have determined the surface density profile of the GCS in the following way. All objects detected down to $V = 25.00$ were binned into annuli concentric about the galaxy center, each annulus being 12″ in width. Each radial annulus was then corrected for incompleteness using the completeness curves determined from the ADDSTAR experiments. We implicitly assume that there is no radial dependence of the completeness fraction, which is reasonable given the lack of crowding in our frames and our exclusion of the central 20″. The surface density of background objects to the same limiting magnitude was then subtracted from each radial bin.

The final surface density profile is shown in Figure 2. In that figure, the dotted line is a least-squares fit to the data, while the solid curve represents the g surface brightness profile of NGC 4073 as derived by Thuan & Romanishin (1981), with arbitrary vertical scaling. Our initial impression of a centrally concentrated GCS is confirmed in Figure 2. The least-squares line has a slope of -0.95 ± 0.30, with a correlation coefficient of -0.72. However, the halo light has a slope of ~ -2, and thus the NGC 4073 GCS is significantly less centrally concentrated than the halo light, a result which has been found for many other galaxies, most notably M87. In fact, the NGC 4073 GCS

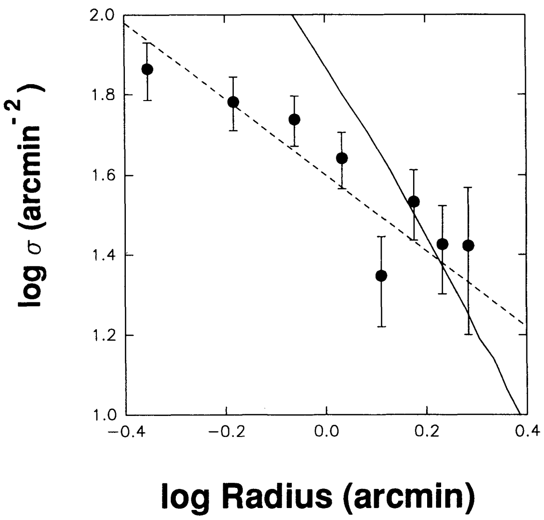

FIG. 2.—Background-subtracted surface density profile of the NGC 4073 GCS. The number density σ is plotted against galactocentric radius (in arcminutes). The dashed line represents a least-squares fit to the globular cluster data, while the solid curve is the g surface brightness profile of NGC 4073 from Thuan & Romanishin (1981), with arbitrary vertical scaling. The data have been corrected for background contamination.

has one of the flattest density profiles found to date, supporting the suggestion by Harris (1986) that the profile slope depends on galaxy luminosity.

3.4.2. *The Globular Cluster Luminosity Function*

We have derived the globular cluster luminosity function (GCLF) of objects detected around NGC 4073 in the usual fashion (see, e.g., our discussion in Bridges & Hanes 1992). For each of the galaxy and background frames, all detected stellar objects down to $V = 25.00$ (the 50% completeness level) were grouped into 0.2 mag bins, each bin being corrected for incompleteness; the 0.2 mag bins were then rebinned into 0.4 mag bins. The background LF, scaled to the same total area, was then subtracted from the galaxy LF, and the resulting background-subtracted LF is shown in Figure 3. In that figure, the solid curve is a Gaussian with $\sigma = 1.4$ and $V_0 = 27.3$ (see below; the faintest data points in Figs. 3 and 4 correspond to a completeness level of 50%).

Figure 3 gives the most convincing proof that we have actually detected a GCS around NGC 4073. In particular, note that we start detecting objects at $V \simeq 23.0$–23.5, which is just what we would expect if the NGC 4073 GCLF is similar to that of the Virgo gEs. In Virgo, clusters are first detected at $V \simeq 20.0$, and, if NGC 4073 is $\sim$4.6 times further (assuming the distance ratio is given by the redshift ratio, corrected for Virgo infall) or $\sim$3.3 mag fainter, than we should indeed start seeing clusters in NGC 4073 at $V \sim 23.3$. The turnover in the GCLF of the Virgo gEs at $V \sim 24.0$ would then correspond to $V \sim 27.3$ at the distance of NGC 4073, and thus our 50% completeness limit is $\sim$2.5 mag brighter than the turnover in the NGC GCLF.

In Figure 4 we have plotted the NGC 4073 GCLF together with the composite Virgo gE GCLF as derived by Harris et al. (1991). The NGC 4073 GCLF has been shifted horizontally by 2.5 mag [a distance shift of 3.3 mag, combined with an assumption that $(B-V) = 0.800$; note we are now plotting log number vs. B magnitude] and scaled vertically by eye. There appears to be reasonable agreement between the two LFs in the limited

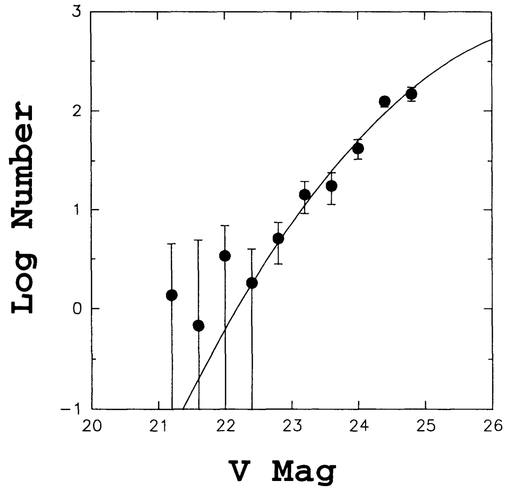

FIG. 3.—Background-corrected GCLF for NGC 4073. Log number is plotted against V magnitude. The solid curve is a nonlinear least-squares fit, with the dispersion σ and the turnover magnitude V_0 fixed at 1.40 and 27.30 mag, respectively. The faintest data point ($V = 24.8$) corresponds to a completeness of 50%.

range of overlap. To test this apparent consistency, we have carried out a least-squares fit of the NGC 4073 GCLF to a Gaussian: $N = N_0 e^{-(V-V_0)^2/2\sigma^2}$. A full fit, where all of N_0, V_0, and σ are allowed to vary, gives $\sigma = 1.40$ and $V_0 = 27.40$; the reduced χ^2 of this fit is $\chi^2_\nu = 1.097$ ($\nu = 7$), which implies a 40% probability that the GCLF is indeed drawn from the specified Gaussian distribution. Monte Carlo simulations show that the corresponding uncertainties in σ and V_0 are ± 0.10 and ± 0.50 mag, respectively. A restricted fit, where σ and V_0 are fixed to be 1.40 and 27.3 (see Fig. 3), yields a $\chi^2_\nu = 0.964$ with a corresponding probability of 50%.

Thus, the NGC 4073 GCLF is adequately consistent with that of the Virgo gEs, if the Virgo GCLF is scaled appropriately in distance. As has been noted before, it is indeed remarkable that the GCLF is similar in so many different environments (extending from field galaxies, to poor clusters, and up to rich galaxy clusters) and over such a range in galactic luminosity (from dEs to the very luminous gE/cD galaxies). This result must be explained by any theory of globular cluster formation (see Harris 1988, 1991).

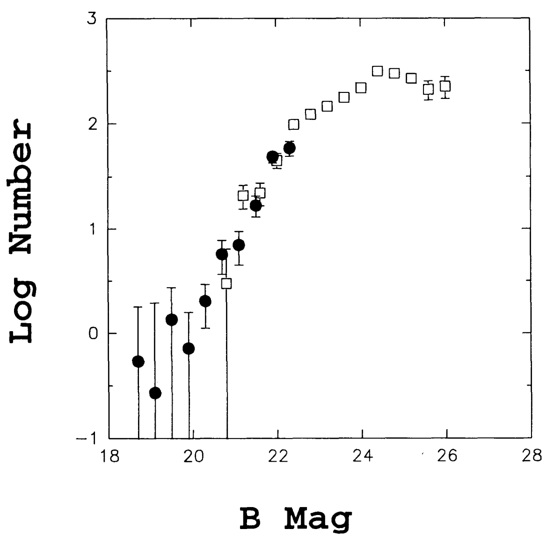

FIG. 4.—NGC 4073 and Virgo GCLFs superposed. Log number is plotted against B magnitude. The squares represent the data for the Virgo gE galaxies from Harris et al. (1991), while the circles represent the NGC 4073 data (Fig. 3), shifted horizontally by 2.5 mag and scaled vertically by eye to fit the Virgo data.

3.4.3. *The Specific Frequency of the NGC 4073 GCS*

For the reasons described in § 1, the specific frequency of the GCS of NGC 4073 is of particular interest. Unfortunately, if the NGC 4073 GCLF is similar to that of the Virgo gEs, we have sampled only ~1.5 mag of the LF, and any specific frequency determination will involve a large extrapolation to estimate the number of clusters fainter than our limiting magnitude. However, we will proceed in the usual way by assuming that the NGC 4073 and Virgo GCLFs are indeed intrinsically similar (i.e., have the same turnover magnitude and dispersion). We also assume that the relative distance modulus is given by the redshift ratio (corrected for Virgo infall), which corresponds to $\Delta V = 3.3 \pm 0.2$. We take the turnover in the Virgo GCLF to be $V = 24.0 \pm 0.2$ and the dispersion σ to be 1.4 ± 0.2 (Harris et al. 1991). In NGC 4073 (see Fig. 3), there are 360 ± 20 objects above background (assumed to be globular clusters) to $V = 25.0$; this $V_{\rm lim}$ corresponds to $V = 21.7 \pm 0.2$ at Virgo. In other words, we are 2.3 ± 0.3 mag or $1.65 \pm 0.3\ \sigma$ short of the turnover; we must then multiply by 20 ± 14 to obtain the total number of clusters over all magnitudes. Thus

$$N_{\rm TOT} = (360 \pm 20)(20 \pm 14) = 7200 \pm 5000 \quad (70\%) .$$

Note that this is a lower limit because we have not included clusters outside our CCD field; however, this will be a small correction due to the relatively large field size at the distance of NGC 4063 (~75 kpc for $H_0 = 75$ km s^{-1} Mpc^{-1}).

Next, we take the apparent total V magnitude of NGC 4073 to be 11.4 ± 0.20 (RC3), and we take $H_0 = 75 \pm 25$ km s^{-1} Mpc^{-1}. We then have all the information we need, and calculate that

$$S_N = 4 \pm 4 .$$

The generous uncertainty in S_N includes uncertainties in H_0, V_T, σ, and the Virgo turnover magnitude. We see that NGC 4073 has a specific frequency comparable to that of the Virgo *normal* gEs (where $S_N \sim 5$–6; Harris 1991), but that S_N is most unlikely to be as high as that for M87. We will discuss the significance of this result in § 4.

3.5. *Results for AWM 3, MKW 12, and AWM 2*

Visual inspection of our CCD images suggests that we have not detected GCSs around the cD galaxies in our other three clusters. A full analysis, similar to that done for NGC 4073/MKW 4 above, confirms this impression for NGC 5629/AWM 3 and NGC 5424/MKW 12. For instance, in Figure 5 we show the background-subtracted radial density profile for the NGC 5629 field; there is no significant central concentration of objects. In Figure 6 we present the background-subtracted GCLF for NGC 5629 down to $V = 24.4$ (the 50% completeness level); again there is no globular cluster "signal." Indeed, such nondetections are not surprising, given that these three galaxies are at roughly the same distance as NGC 4073, but have lower total exposure times (see Table 2) and are all intrinsically less luminous than NGC 4073. We did not carry out a comparably full analysis for NGC 4213/AWM 2, given its even

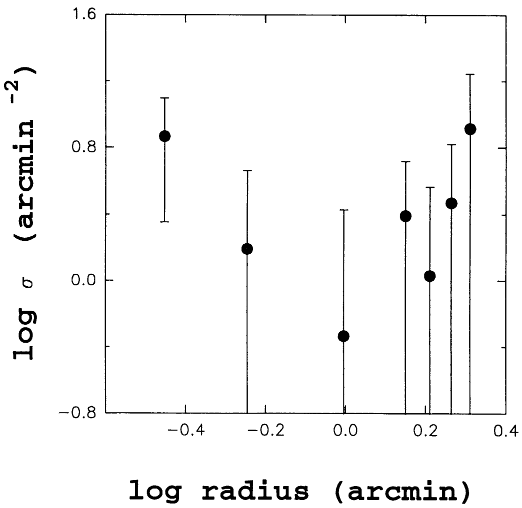

FIG. 5.—Background-subtracted surface density profile for the NGC 5629 GCS. Log σ is plotted against galactocentric radius (in arcminutes). There is no evidence for a central concentration of objects.

higher recession velocity, short exposure time, and lack of any central concentration among the limited numbers of objects detected; our conclusions below should be regarded as more tentative for this system.

We have used these nondetections to determine upper limits for the specific frequency of any GCSs in these three galaxies. We must first determine the number of globular clusters that would have been observed for a given specific frequency S_N and absolute galaxy luminosity M_V: $N = S_N \times 10^{-0.4(M_V+15)}$ (for the determination of M_V, we use the apparent magnitude V and take H_0 to lie in the range 50–100 km s^{-1} Mpc^{-1}). This gives the total number of clusters expected over all magnitudes. We next assume that any putative GCS in attendance would have a Gaussian LF with a dispersion in the range 1.25–1.50 (values found for observed GCLFs; e.g., Harris 1991) and that the apparent turnover in the GCLF can be simply scaled from that of the Virgo gEs (where $V_0 \simeq 24.0$) using the distance

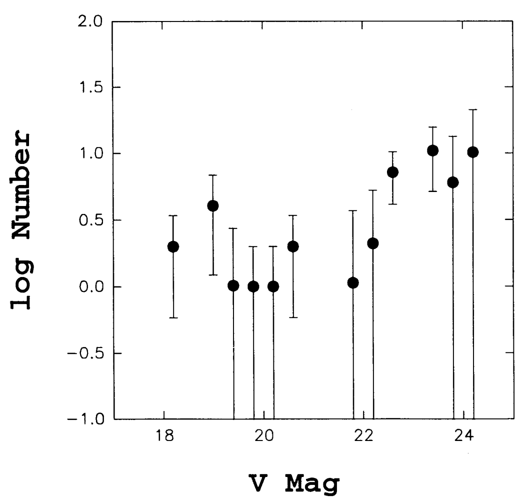

FIG. 6.—Background-corrected GCLF for NGC 5629. Log number is plotted against V magnitudes. The faintest data point represents the 50% completeness level. There is no evidence for a rising luminosity function which would indicate the detection of a GCS. (If the NGC 5629 GCS was similar to that of the Virgo gEs, we would have expected to see clusters starting to appear between $V = 22$ and 23.)

(velocity) ratios between our galaxies and that of M87/Virgo. We then compute the number of clusters expected to the limiting magnitudes determined for our galaxy frames. This final number is then compared to the number of background-subtracted objects actually found in our frames (to the same magnitude level), and upper limits are placed on S_N.

One sees that there are many uncertainties entering the above analysis (in H_0, GCLF dispersion, and $V_{\rm lim}$). For NGC 5424, we have also had to estimate the contamination by foreground Galactic stars (using the models of Bahcall & Soneira 1981), since we do not have an independent background frame for this galaxy. In addition, the relatively shallow limiting magnitudes and large recession velocities for these three galaxies imply that we would expect to see very few clusters (<100) even for relatively large values of S_N. Thus, it is difficult to put precise upper limits on S_N for these galaxies. The "moral of the story" is that one needs to reach at least to $V \sim 25$ for galaxies at these distances and further, except of course that superabundant systems will be unambiguously detected.

However, we may summarize our calculations by saying that we are confident that $S_N < 10$ (2 σ upper limits are $S_N < 5$ for NGC 5629 and $S_N < 10$ for NGC 5424) for all three galaxies. Thus, *it is most unlikely that any of the four cD galaxies we have studied here has a superabundant GCS* (cf. M87/Virgo, NGC 1399/Fornax, and NGC 3311/Hydra, where S_N = 15–20). This is a very important result, and we discuss its consequences below.

4. DISCUSSION AND INTERPRETATION

To summarize briefly: we have detected a GCS around NGC 4073, the cD galaxy in MKW 4, and determined its specific frequency to be $S_N = 4 \pm 4$. As is commonly observed in other galaxies, the NGC 4073 clusters are less centrally concentrated than the halo light (projected density profile $\propto r^{-1}$ and r^{-2}, respectively). In contrast, we have not detected a GCS around the cDs in AWM 3, MKW 12, and AWM 2 and can set upper limits of S_N < 5–10 for their specific frequencies.

4.1. *Rich versus Poor Clusters*

We begin by recapitulating the nature of the GCSs associated with central galaxies in rich clusters. It is surely revealing that the four gE/cD systems with superpopulous GCSs (M87/Virgo, NGC 3311/Hydra, NGC 1399/Fornax, and possibly NGC 4874/Coma) are all centrally located in such rich clusters. No high-S_N system has been found in smaller groups, or in a noncentral position, and there are no known examples of two high-S_N systems in one cluster.

Intriguingly, however, two of the high-S_N systems (M87 and NGC 4874) are *not* the brightest galaxies in their respective clusters. In both Virgo and Coma, there appear to be two main subclusters, with M87 (Virgo) and NGC 4874 (Coma) at the centers of one subcluster, and the brightest cluster galaxies, M49 (Virgo) and NGC 4889 (Coma), at the centers of the other. However, both M87 and NGC 4874 are closer to the mean cluster velocity and to the center of the galaxy counts. As well, the Virgo X-ray emission is centered on M87, and NGC 4874 is a central radio source in Coma (the Coma X-ray emission is quite smooth and broadly distributed, and there appears to be no excess emission associated with either NGC 4874 or NGC 4889). Butterworth & Harris (1992) recently detected a GCS around the gE NGC 3842, which is the brightest galaxy in Abell 1367, a richness class II cluster at a recession velocity of

6500 km s^{-1}. NGC 3842, however, appears to be significantly offset from the center of A1367, and its specific frequency is inferred to be $S_N \simeq 7$–8, consistent with the above picture.

On the other hand, recent studies have also made it clear that central location in a rich cluster environment is not in itself sufficient for the production of high-S_N systems. Pritchet & Harris (1990) studied the cD galaxy NGC 6166, which is centrally located in the rich cluster Abell 2199, yet which has a specific frequency $S_N \sim 4$. More recently, Harris, Pritchet, & McClure (1993) have looked at a sample of three quite remote ($cz \sim 10{,}000$ km s^{-1}) cD galaxies in rich Abell clusters. They conclude that two of these galaxies (UGC 9799 in A2052 and UGC 9958 in A2107) are likely to contain high-S_N cluster systems, whereas the third (NGC 7768 in A2666) almost certainly does not; these conclusions must unfortunately be regarded as quite tentative due to the remoteness of these systems. As Harris et al. note, the specific frequencies for gE/cD galaxies (in rich clusters) do not show any strong correlations with the size of the cD envelope, total galactic luminosity, galaxy cluster richness, or X-ray luminosity.

Our work on poor cluster cDs adds a new dimension to this discussion. As we show above, the poor cluster cDs we have studied are all centrally located, with NGC 4073 being more luminous than M87; moreover, MKW 4 is a brighter X-ray source than Virgo. Nonetheless, only one of the systems studied appears to have even a detectable GCS, much less a superabundant one. However, Virgo is a richer cluster environment than any of the MKW/AWM objects, so perhaps a *globally rich* environment is needed for the production of high-S_N systems, along with an as-yet-unknown "second parameter."

West (1993) has recently developed a general model of "biased" globular cluster formation. By assuming that globular clusters only form from rare high-density peaks in the primordial matter distribution, and with some additional assumptions about the biasing process, he is able to explain the observed dependence of globular cluster specific frequency on galaxy type and environment. The model may also be able to explain the observed uniformity of the GCLF, and it certainly deserves further exploration. However, the model does not make any new predictions, and it is not clear whether it (or any pregalactic formation model) can explain disk clusters and the spatial metallicity gradients observed in many GCSs.

4.2. *The Role of Cooling Flows*

Our results also support earlier suggestions (e.g., Pritchet & Harris 1990) that cooling flows are not a primary producer of globular clusters. NGC 4073/MKW 4 has an inferred cooling flow comparable to or slightly larger than that of M87/Virgo, yet their specific frequencies are much different. A similar conclusion was reached by Pritchet & Harris in their study of NGC 6166, which as a cooling flow ~80 times larger than M87, yet has a specific frequency $S_N \leq 4$. There are other arguments against cooling-flow formation models (see also Harris 1991). First, M87 globular clusters are quite similar to those in the normal Virgo galaxies, both photometrically (Cohen 1988; Couture, Harris, & Allwright 1990) and spectroscopically (Mould, Oke, & Nemec 1987; Mould et al. 1990). In addition, the mean metallicity of the X-ray halo gas (e.g., Mushotzky 1984) is much higher than that of globular clusters in these galaxies (e.g., Mould et al. 1990). If cooling flows have formed globular clusters continuously up to the present, it is hard to explain the above observations.

On the other hand, cluster cooling flow rates may have been much higher in the past, and perhaps the bulk of globular clusters were formed long ago when the X-ray gas had a lower metallicity (an early cluster formation epoch is also implied by other observations; see the discussion in Harris 1991) Moreover, in other clusters cooling flows may have been disrupted by the merger of subclusters (e.g., Coma). In the present data, it is perhaps significant that MKW 4, a poor cluster cD with a cooling flow, has a detectable GCS, while MKW 12 and AWM 3, with no cooling flows, do not. Our admittedly small sample, then, provides data which are consistent with a picture in which cooling flows contribute at some small level. More data, especially for clusters with large cooling flows, are needed.

4.3. *Mergers and Interactions*

One of the strongest arguments against a merger origin for ellipticals has been the "specific frequency problem," namely that ellipticals have higher globular cluster specific frequencies than do their alleged spiral progenitors (e.g., van den Bergh 1990). However, this problem can be alleviated if significant numbers of globular clusters can be formed during the merger itself.

Indeed, there have been several recent discoveries of probable young globular clusters in merging systems. For example, in a study of NGC 3597, a strongly interacting system, Lutz (1991) found a number of bright ($M_V \sim -13$), blue [$0.1 \leq (V-R) \leq 0.5$] objects which he tentatively identified as being young globular clusters. Unfortunately, the spatial resolution (~100 pc) was not high enough to permit a clear discrimination between H II–like regions and more compact star clusters. Then, using the *HST* WF/PC, Holtzman et al. (1992) detected ~50 bright, blue clusters in NGC 1275, the cD in the Perseus cluster. Taking the observed luminosities and colors together with stellar population synthesis models (Charlot & Bruzual 1991), they determined that the clusters are at most ~300 million years old and $\sim 10^7\ M_\odot$. The models suggest that these objects will evolve in 10–20 Gyr to look like present-day "normal" halo globulars. Holtzman et al. concluded that the observed uniformity of the "cluster" colors argues against their formation from the Perseus cooling flow (with $\dot{M} \sim 200\ M_\odot\ yr^{-1}$; Fabian, Nulsen, & Canizares 1991). Instead, they favor cluster formation from a burst of star formation induced by a merger between NGC 1275 and another galaxy a few hundred million years ago; indeed, there is evidence for such a past interaction in the form of ripplelike structures around NGC 1275. Preliminary ground-based results, based on short-exposure CFHT/HRcam images, confirm the blue colors and bright magnitudes of the Holtzmann et al. objects (Richer et al. 1993); unfortunately, the uncertainties in the colors are still ~0.2 mag. Deeper imaging and spectroscopy of cluster candidates will resolve these issues.

Ashman & Zepf (1992) and Zepf & Ashman (1993) have put forward a model in which spirals merge and form a new population of globular clusters at the same time as the elliptical itself. Their model naturally makes the clear observational prediction that GCSs around ellipticals should have bimodal (or multimodal) color/metallicity distributions, since any globular clusters formed during later mergers will be more metal rich (and likely more centrally concentrated) than those clusters formed earlier in the halos of the progenitor spirals. Encouragingly, some existing work is consistent with the Ashman & Zepf model. For instance, M87 and NGC 1399, centrally located gE/cD galaxies which presumably have experienced some interactions, have superabundant cluster systems with a mean cluster [Fe/H] higher than in the Galaxy (Mould et al. 1987, 1990; Geisler & Forte 1990); as well, the dispersion in

[Fe/H] is also higher in these two systems (Harris 1991). There appears to be significant bimodality in the color distributions of the GCSs of the Virgo galaxies NGC 4472 (Couture, Harris, & Allwright 1991; Zepf & Ashman 1993) and M87 (Lee & Geisler 1993), the Fornax cD NGC 1399 (Ostrov, Geisler, & Forte 1993), and NGC 5128 (Harris et al. 1992; Zepf & Ashman 1993). Interestingly, Lee & Geisler (1993) find that the bimodal color distribution of the M87 GCS persists out as far as the cD envelope.

However, our work suggests that few globular clusters are formed during the merger of cluster galaxies, at least within the poor clusters. As discussed above (§ 2.1), one expects mergers to be relatively more important in the evolution of cD galaxies in poor clusters, where the velocity dispersions and cluster sizes are lower. Yet the specific frequencies of the poor cluster cDs apparently do not support the idea that mergers can create large numbers of globular clusters. It will certainly be important to carry out a systematic survey of systems which show strong evidence for interactions to test these predictions further. It will be especially interesting to search for globular clusters in cD/gE galaxies in compact groups, since the dynamical environment of compact groups (high density and low velocity dispersion) should be especially favorable for merging (e.g., Mendes de Oliveira & Hickson 1993). (Preliminary analysis of CFHT data obtained by C. Mendes de Oliveira and M. Bolte [Mendes de Oliveira 1993, private communication] shows that there are no luminous blue "globular clusters" in galaxies in Stephan's Quintet and Seyfert's Sextet.) The semianalytical model of Ashman & Zepf needs to be developed further. Their model cannot, for example, satisfactorily explain why globular cluster–sized objects will *preferentially* be formed during mergers (a necessary happenstance if the specific frequency—the ratio of clusters to field stars —is to increase as a result of the merger). As well, some GCS properties accounted for by the Ashman & Zepf model (spatial metallicity gradients, metallicity offsets between clusters and field stars) can also be explained by formation scenarios which do not involve mergers (e.g., Harris 1986). What is also needed is physically detailed numerical modeling, perhaps using hybrid N-body/gas dynamics codes (e.g., Hernquist & Katz 1989), to see if globular cluster–like objects are naturally formed in sufficient numbers during mergers.

It should finally be noted that the physical conditions present during galactic mergers may be quite similar to those found in the protogalactic collapse phase (e.g., Kang et al. 1990; Shapiro, Clocchiatti, & Kang 1992), in which case the distinction between the two modes of cluster formation is quite blurred and one can imagine both happening together as in certain models of "turbulent" galaxy formation (e.g., Searle & Zinn 1978; Larson 1986; Sandage 1990). A related point is that if mergers are to form sufficient numbers of globular clusters to overcome the "specific frequency problem," such mergers must likely occur at relatively early epochs when the progenitor spirals were still very gas rich.

5. SUMMARY AND CONCLUSIONS

The principal conclusions of the present work are:

1. GCS is detected in only one of the four poor clusters chosen for study: MKW 4. Its specific frequency of $S_N \simeq 4 \pm 4$ is typical of that of an elliptical galaxy in an undistinguished location—the GCS is clearly not superabundant.
2. In the other three poor clusters, upper limits of $S_N < 5$–10 can be set on the specific frequencies of any attendant GCSs.
3. These findings strongly suggest that, despite recent theoretical and observational developments, mergers are not important in the generation of extremely populous GCSs, since the central galaxies in poor clusters presumably have more active merging histories than do their counterparts in richer surroundings. It appears that, for reasons as yet incompletely understood, the global richness of the environment within which the galaxy finds itself is the key determinant.
4. Of the four poor clusters studied, only the one with a moderate cooling flow has a detectable GCS, which may imply that the flow is partly responsible for its formation. Since counterexamples are known, however, the role of the cooling flow remains ambiguous.
5. The GCS associated with NGC 4073, the cD galaxy in MKW 4, is among the least centrally concentrated of any studied to date. This supports a suggestion by Harris (1991) that the degree of central concentration of a GCS is a function of the luminosity of the parent galaxy, with the most luminous galaxies having the most distended cluster systems. The interpretation is still elusive, however, because of the uncertain importance of the merger history of the galaxy.

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REFERENCES

Albert, C. E., White, R. A., & Morgan, M. W. 1977, ApJ, 211, 309 (AWM)
Ashman, K. M., & Zepf, S. E. 1992, ApJ, 384, 50
Bahcall, J. N., & Soneira, R. M. 1981, ApJS, 47, 357
Beers, T. C., Geller, M. J., Huchra, J. P., Latham, D. W., & Davis, R. J. 1984, ApJ, 283, 33
Beers, T. C., Huchra, J. P., Kriessler, J., & Bird, C. M. 1993, in preparation
Binney, J., & Tremaine, S. 1987, Galactic Dynamics (Princeton, Princeton Univ. Press)
Bridges, T. J., & Hanes, D. A. 1992, AJ, 103, 800
Bridges, T. J., Hanes, D. A., & Harris, W. E. 1991, AJ, 101, 469
Burns, J. O., White, R. A., & Haynes, M. P. 1981, AJ, 86, 1120
Butterworth, S. T., & Harris, W. E. 1992, AJ, 103, 1828
Canizares, C. R., Stewart, G. C., & Fabian, A. C. 1983, ApJ, 272, 449
Charlot, S., & Bruzual, A. G. 1991, ApJ, 367, 126
Cohen, J. G. 1988, AJ, 95, 682
Couture, J., Harris, W. E., & Allwright, J. W. B. 1990, ApJS, 73, 671
———. 1991, ApJ, 372, 97
Fabian, A. C., Hu, E. M., Cowie, L. L., & Grindlay, J. 1981, ApJ, 248, 47
Fabian, A. C., Nulsen, P. E. J., & Canizares, C. R. 1991, Astron. Astrophys. Rev., 2, 191
Fischer, P., Hesser, J. E., Harris, H. C., & Bothun, G. D. 1990, PASP, 102, 5
Geisler, D., & Forte, J. C. 1990, ApJ, 350, L5
Hanes, D. A., & Harris, W. E. 1986a, ApJ, 309, 564
———. 1986b, ApJ, 304, 599
Harris, G. L. H., Geisler, D., Harris, H. C., & Hesser, J. E. 1992, AJ, 104, 613
Harris, W. E. 1986, AJ, 91, 822

Harris, W. E. 1987, ApJ, 315, L29
———. 1988, in The Extragalactic Distance Scale, ed. S. van den Bergh & C. J. Pritchet (ASP Conf. Ser., 4), 231
———. 1991, ARA&A, 29, 543
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. Smith & J. Brodie (ASP Conf. Ser., 48), 572
Harris, W. E., & Smith, M. G. 1976, ApJ, 207, 1036
Harris, W. E., Smith, M. G., & Myra, E. S. 1983, ApJ, 272, 456
Harris, W. E., & van den Bergh 1981, AJ, 86, 1627
Hernquist, L., & Katz, N. 1989, ApJS, 70, 419
Hintzen, P. 1980, AJ, 85, 626
Holtzmann, J. A., et al. 1992, AJ, 103, 691
Kang, H., Shapiro, P. R., Fall, S. M., & Rees, M. J. 1990, ApJ, 363, 488
Kriss, G. A., Cioffi, D. F., & Canizares, C. R. 1983, ApJ, 272, 439
Larson, R. B. 1986, MNRAS, 218, 409
Lee, M. G., & Geisler, D. 1993, AJ, 106, 493
Lutz, D. 1991, A&A, 245, 31
Malumuth, E. M., & Kirshner, R. P. 1985, ApJ, 291, 8
Malumuth, E. M., & Kriss, G. A. 1986, ApJ, 308, 10
Mendes de Oliveira, C., & Hickson, P. 1993, preprint
Morbey, C., & Morris, S. 1983, ApJ, 274, 502
Morgan, W. W., Kayser, S., & White, R. A. 1975, ApJ, 199, 545 (MKW)
Mould, J. R., Oke, J. B., de Zeeuw, P. T., & Nemec, J. M. 1990, AJ, 99, 1823
Mould, J. R., Oke, J. B., & Nemec, J. M. 1987, AJ, 93, 53
Mushotzky, R. F. 1984, Phys. Scripta, T7, 157
Muzzio, J. C. 1987, PASP, 49, 245
———. 1988, in The Harlow Shapley Symposium on Globular Cluster Systems in Galaxies, ed. J. E. Grindlay & A. G. D. Philip (Dordrecht: Kluwer), 297
Ostrov, P., Geisler, D., & Forte, J. C. 1993, AJ, 105, 1762
Price, R., Burns, J. O., Duric, N., & Newberry, M. V. 1991, AJ, 102, 14
Pritchet, C. J., & Harris, W. E. 1990, ApJ, 355, 410
Quintana, H., & Lawrie, D. G. 1982, AJ, 87, 1
Richer, H. B., Crabtree, D. R., Fabian, A. C., & Lin, D. N. C. 1993, AJ, 105, 877
Rood, H. J., & Sastry, G. N. 1971, PASP, 83, 313
Sandage, A. 1990, JRASC, 84, 70
Schweizer, F., & Seitzer, P. 1993, ApJ, 417, L29
Searle, L., & Zinn, R. 1978, ApJ, 225, 357
Shapiro, P. R., Clocchiatti, A., & Kang, H. 1992, ApJ, 389, 269
Stauffer, J., & Spinrad, H. 1990, ApJ, 235, 347
Struble, M. F., & Rood, H. J. 1991, ApJ, 363, 49
Thomas, J. C., & Batchelor, D. 1978, AJ, 83, 1160
Thompson, L., & Valdes, F. 1987, ApJ, 315, L35
Thuan, T. X., & Romanishin, W. 1981, ApJ, 248, 439
van den Bergh, S. 1975, PASP, 89, 746
———. 1990, in Dynamics and Interactions of Galaxies, ed. R. Wielen (Berlin: Springer), 492
West, M. J. 1993, MNRAS, 265, 755
Whitmore, B. C., Schweizer, F., Leitherer, C., Borne, K., & Robert, C. 1993, AJ, 106, 1354
Zepf, S. E., & Ashman, K. M. 1993, MNRAS, 264, 611