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GLOBULAR CLUSTERS AND cD FORMATION: THE CASE OF M87

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ABSTRACT

New wide-field CCD photometry around M87 is used to define the radial profile for its globular cluster system over the region 1′.2 ≲ R ≲ 9′.2. The best-fit de Vaucouleurs profile clearly shows an excess of clusters beginning at R ∼ 4′.5, just where the cD envelope of the M87 halo begins. We find that this "extra" cD component of the globular cluster population has the same high specific frequency as the main body of M87 does; this result is used to argue for an epoch of cD envelope formation which precedes both astration of the envelope and relaxation of the Virgo Cluster itself.

Subject headings: galaxies: formation — galaxies: individual (M87) — galaxies: star clusters

1. INTRODUCTION

The enormously populous and spatially extensive globular cluster system (GCS) around M87 has been the focus of many studies concentrating on the systemic properties of these objects. Some early investigations (e.g., Harris & Smith 1976; Strom et al. 1981) examined the GCS over a large range of galactocentric radius via photographic photometry; in contrast, the more recent CCD studies of, for example, Grillmair, Pritchet, & van den Bergh (1986) and Cohen (1988), although reaching to considerably deeper limiting magnitudes, have been constrained by smaller field sizes. In this *Letter* we present new data for the large-scale structure of the M87 cluster system, from *wide-field* CCD imaging that regains the advantages of the photographic surveys while retaining the depth and linearity of CCD photometry. Our main result is the discovery of interesting structure in the outer halo of the GCS and its implications for the epoch of formation of the cD envelope in M87.

2. OBSERVATIONS AND REDUCTIONS

Our new data were obtained on the night of 1991 February 20 with the ST2K CCD at the prime focus of the KPNO 4 m telescope. The useful area of the chip is 2012 × 2044 pixels; at a scale of 0″.42 pixel^{-1}, this gives a field which is ∼14′ on a side. Three exposures were taken in the V band and then averaged to make the final image, with a total exposure time of 2400 s. Unfortunately, time limitations prevented us from obtaining a separate background field. The field is roughly centered on M87, resulting in complete areal coverage of the galaxy's halo to a projected radius of 6′.7, and partial coverage out to R ∼ 9′.2. Because the goal here was to obtain information about the GCS at large radii, the innermost region was allowed to become saturated; this effect, coupled with severe crowding, led us to ignore from the outset all data inside a radius of 1′.21 from the center of the galaxy.

After preprocessing, the image was reduced via the standard IRAF implementation of DAOPHOT (Stetson 1987). It proved necessary to divide the frame into four large subimages, because of a noticeable variation of the PSF structure across the frame (in particular, the Gaussian core of the PSF is spherical in the central regions, with a FWHM of ∼1″.25, but becomes broader and more elliptical toward the edges of the image). Each of these four subsections was then subjected to identical reduction procedures (aside from the use of different PSFs). To remove the background galaxy light, we adopted an iterative median-filtering process (Fischer et al. 1990), whereby the objects found with DAOPHOT's DAOFIND routine are subtracted from the original frame by ALLSTAR, and the residual image is median-filtered; this filtered "galaxy" is then subtracted from the original frame, and the process repeated. The instrumental magnitudes were then calibrated by same-night photometry of numerous standard stars, with a resulting zero-point uncertainty $\epsilon(V)$ of ±0.03 mag.

Extensive artificial-star tests showed that the completeness limit differs among the four subimages, due to the varying characteristics of the PSF; it is also a function of radius within ∼3′ of the center of the galaxy because of crowding, but *in general*, the data are 100% complete to $V = 23$, and better than 50% complete to $V \simeq 24$. Finally, to remove obvious faint background galaxies from our starlists, we applied an automated classification scheme (Harris et al. 1991), using the two moments r_{-2} (a measure of central concentration) and ΔV (the difference between the ALLSTAR PSF magnitude and an aperture magnitude) to distinguish nonstellar objects.

After this, we were left with a catalog of some 4000 starlike objects brighter than $V = 24$ before correction for incompleteness. Those brighter than $V = 23$ are displayed in Figure 1. (A modified reproduction of our composite image can be seen on the cover of the 1992 August issue of the PASP.) The apparent paucity of detections in the area east of $X = 450$ pixels in Figure 1 is an artifact of the degraded PSF and poorer photometry in that region (i.e., the data are *not* complete to $V = 23$ here); the information from this part of the frame has therefore been discarded. Thus we have in the end ∼3600 detections brighter than $V = 24$, and a total usable area of ∼165 arcmin^2.

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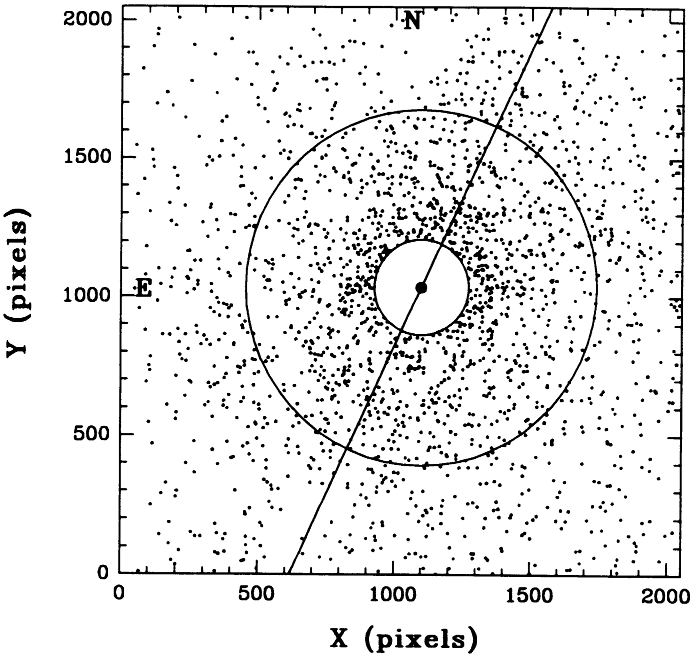

FIG. 1.—Distribution of *starlike* objects around M87 brighter than $V = 23$, to which limit our data are essentially 100% complete. The large dot is the adopted center of the galaxy. The inner circle has a radius of 1.'21, within which crowding and saturation render the CCD exposure unusable. The larger circle (radius 4.'5) marks the onset of the cD envelope and the excess in the globular cluster surface density profile. For orientation, the projected semimajor axis of the galaxy isophotes is also indicated (155° E of N; C&D).

3. ANALYSIS

We bin the final starlist simultaneously in magnitude, in projected galactocentric radius, and in azimuthal distance from the projected major axis of the galaxy isophotes. The counts in each bin are then corrected for incompleteness. Details of the resulting globular cluster luminosity function (GCLF) and azimuthal profile will be presented in a later paper (McLaughlin, Harris, & Hanes 1993). Here we discuss the surface density profile, constructed by taking number counts in a series of circular annuli about the galaxy center for the magnitude range $20 \leq V \leq 24$. As mentioned above, we do not have same-night photometry of an adjacent background field; therefore, in order to extract from the raw counts a *self-consistent* estimate of the background surface density, we follow the method of Harris (1986), which relates the asymptotic value of the best-fit $R^{1/4}$ law to the true background. In this way, we find $\sigma_b = 6.3 \pm 0.4$ arcmin^{-2}; this value is then subtracted from the density in each radial bin to give the projected radial profile of the GCS, as presented in Table 1. The characteristic radius of each annulus is taken to be the geometric mean of the inner and outer radii (Harris 1986), and the quoted errors combine the Poisson noise of the number counts with the binomial uncertainty of the completeness function (Bolte 1989).

A simple empirical fitting function, and the one which provides the best scale-free measurement of the systemic central concentration, is a power law $\sigma_{cl} = kR^{-\alpha}$. A nonlinear least-squares fit to our entire data set gives (for σ_{cl} in units of arcmin^{-2}) $\log k = 2.18 \pm 0.03$ and $\alpha = 1.47 \pm 0.06$. The exponent agrees well with $\alpha \simeq 1.6$ (Harris 1986) and $\alpha \simeq 1.5$ (Cohen 1988), and confirms that the GCS is considerably more extended than the halo light, for which $\alpha \simeq 1.9$ (de Vaucouleurs & Nieto 1978, hereafter dVN).

TABLE 1

GCS SURFACE DENSITY PROFILE

Annulus	Mean Radius	Number[a]	Area[b] (arcmin^2)	σ_{cl}[c] (arcmin^{-2})
1.'21–1.'40..........	1.'30	173 ± 16	1.54	106.00 ± 10.27
1.40–1.62..........	1.50	178 ± 16	2.05	80.53 ± 7.99
1.62–1.87..........	1.74	239 ± 18	2.72	81.57 ± 6.75
1.87–2.16..........	2.01	209 ± 16	3.63	51.28 ± 4.46
2.16–2.49..........	2.32	220 ± 16	4.79	39.63 ± 3.42
2.49–2.88..........	2.68	281 ± 19	6.42	37.47 ± 2.93
2.88–3.32..........	3.09	297 ± 18	8.60	28.23 ± 2.15
3.32–3.83..........	3.57	334 ± 20	11.48	22.79 ± 1.73
3.83–4.43..........	4.12	365 ± 21	15.28	17.59 ± 1.40
4.43–5.11..........	4.76	436 ± 24	18.58	17.17 ± 1.29
5.11–5.90..........	5.49	431 ± 25	21.34	13.90 ± 1.18
5.90–6.82..........	6.35	441 ± 26	26.63	10.26 ± 0.98
6.82–7.87..........	7.33	291 ± 21	21.08	7.51 ± 1.01
7.87–9.09..........	8.46	84 ± 11	7.79	4.48 ± 1.46

[a] Raw number counts, corrected for photometric incompleteness, but not for the presence of background objects.

[b] Area in the frame-annulus intersection, after correcting for the area occupied by saturated stars, obvious large galaxies, and other similar "excised" objects.

[c] Number density of the GCS alone, i.e., after subtraction of the background, $\sigma_b = 6.3$ arcmin^{-2}.

However, it is the standard de Vaucouleurs profile, $\sigma_{cl} = A \times 10^{-aR^{1/4}}$, which gives us the most insight. In Figure 2 we show our entire GCS density profile and the galaxy light profile of dVN, along with the best-fit $R^{1/4}$ law for each, where the fits have been made to the data *inside* $R = 4.'5$ ($R^{1/4} = 1.46$). In the halo intensity profile, the well-defined excess of light over the basic $R^{1/4}$ law, beginning at $R \simeq 4.'5$, is the classic signature of a cD envelope or corona. Our GCS data reveal essentially the same phenomenon: starting sharply at $R \sim 4.'5$, more clusters are found than predicted by an extrapolation of the $R^{1/4}$ profile defined by the inner GCS. The most logical interpretation to us is that for the first time we are seeing the distinct trace of the M87 cD envelope *in the globular cluster system.*

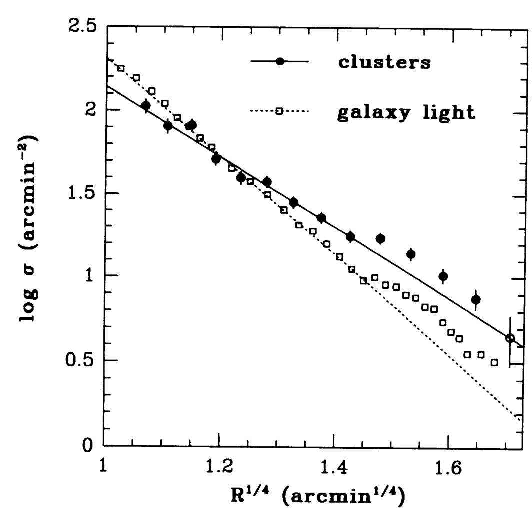

FIG. 2.—Surface density profile of the globular cluster system (*filled circles*), compared with the (arbitrarily shifted) galaxy surface brightness profile of dVN (*open squares*). The solid line is the $R^{1/4}$ profile which describes the globular cluster system inside $R = 4.'5$ ($a = 2.12$ arcmin$^{-1/4}$), while the dashed line is the best-fit $R^{1/4}$ law ($a = 3.0$ arcmin$^{-1/4}$) for the *halo light* in the same region, according to dVN. The outermost GCS data point (*open circle*) has been excluded from the analysis in the text.

The size of this effect is obviously sensitive to the choice of background surface density. However, the adopted σ_b is unlikely to be an *underestimate* of the true background. In fact, experimentation with the GCS counts of Harris (1986), which extend to still larger radii, suggests that we may have *overestimated* the background by $\sim 25\%$, in which case the GCS cD envelope is even more substantial than we find here. Realizing this, we exclude from subsequent discussion the outermost data point (at $R = 8'46$, $R^{1/4} = 1.71$), which would be the most affected by a background error. We have ruled out the possibility that we are actually seeing a cluster of background galaxies, by identifying the envelope in all directions around the galaxy. Furthermore, the effect seems not to depend on magnitude: it shows up in the separate intervals $20 \leq V \leq 23$ and $23 \leq V \leq 24$; and our complete analysis of the GCLF shows no significant variations with radius (McLaughlin et al. 1993).

These new data give us the first opportunity to compute a specific frequency (the number of globular clusters per unit halo light: Harris & van den Bergh 1981) *for the cD envelope*, as distinct from the main body of the galaxy. The specific frequency, defined as $S_N = N_t \times 10^{0.4(M_V{}^T + 15)}$ where N_t is the total population of the GCS and M_V^T is the galaxy luminosity, is a direct tracer of the cluster formation efficiency in the given region. For our purposes here, the quantity of interest is the *ratio* of the specific frequency of the cD envelope to that of the underlying galaxy component, $\beta \equiv S_N^{\rm env}/S_N^{\rm gal}$. If we denote the normalized GCLF by $\phi(V)$, the limiting magnitude by $V_{\rm lim}$, and the galaxy's integrated apparent magnitude by B^T, then we have quite generally

$$\beta = \frac{N_{\rm env}}{N_{\rm gal}} \frac{f_{\rm gal}}{f_{\rm env}} 10^{0.4\Delta B^T} 10^{-0.4\Delta(B-V)} , \qquad (1)$$

where $\Delta B^T = B^T_{\rm env} - B^T_{\rm gal}$, $\Delta(B-V) = (B-V)_{\rm env} - (B-V)_{\rm gal}$, and $f = \int_{-\infty}^{V_{\rm lim}} \phi(V)dV$. $N_{\rm env}$ and $N_{\rm gal}$ are just the observed numbers of clusters in each component corrected for photometric incompleteness. Clearly, β is independent of the assumed distance, and as long as the galaxy and envelope components of the GCS have the *same* LF, its particular form is irrelevant.

We first calculate the specific frequency of the entire GCS (i.e., including the envelope) between $R = 1'21$ and $7'87$. The Virgo distance modulus is assumed to be 31.0 (Jacoby et al. 1992); $(B-V)$(M87) = 1.0 (Carter & Dixon 1978, hereafter C&D); and the GCLF is presumed to be Gaussian in form, with a peak at $V^0 \approx V_{\rm lim} = 24.0$ (Harris et al. 1991), so that $f \approx 1/2$. The integrated B^T of the halo light over the same radial region is computed from the dVN profile, yielding finally $S_N \gtrsim 14$. This result compares well with $S_N = 14 \pm 4$ (Harris 1986) and $14 < S_N < 25$ (Grillmair et al. 1986).

Next we consider the "global" value of β, where $N_{\rm gal}$ is taken from the entire range $R = 1'21$–$7'87$ (minus the excess counts from the cD envelope) and where $N_{\rm env}$ is taken from $R = 4'43$ to the same outer radius. The separate B^T magnitudes of the envelope and the galaxy are again derived directly from the dVN profile. Equation (1) then gives us $\beta_{\rm global} = 1.3 \pm 0.3$. This result tacitly involves the secondary assumptions that $\Delta(B-V) = 0$ (C&D) and $f_{\rm env} = f_{\rm gal}$. The latter supposition, though crucial to the result, is supported directly by our GCLF analysis (McLaughlin et al. 1993). The assumption $\Delta(B-V) = 0$ is less critical: to change β by a factor of 2, given $f_{\rm gal} \approx f_{\rm env}$, we would require an unrealistically large color difference ($|\Delta(B-V)| \sim 0.75$).

Finally, we consider the ratio β for the envelope region alone (i.e., where $N_{\rm gal}$ and B^T are calculated for only the outer region $R = 4'43$–$7'87$). We find $\beta_{\rm env} = 0.8 \pm 0.2$. This local value is unambiguously smaller than $\beta_{\rm global}$ because the GCS has a larger effective radius than the galaxy light and the local value of $S_N^{\rm gal}$ increases with radius. However, the main point is that the values of both $\beta_{\rm global}$ and $\beta_{\rm env}$ are consistent with unity, and therefore that *the cD envelope is a high–S_N system.* If the envelope component had a "normal" S_N value of ~ 5 (Harris 1991), we would have found $\beta \approx 0.4$ and an almost undetectable GCS excess population in Figure 2.

4. DISCUSSION

The spatial profiles and sizes of most cD galaxies favor the interpretation that cD *envelopes* are distinct structures that were added on to the body of a preexisting large galaxy (e.g., Schombert 1988; Mackie 1992). Two basic approaches have been extensively developed in the literature to explain their existence. In the first scenario, much of the mass in a cluster of galaxies after virialization is initially in the galaxies themselves; then the time scale for collisional stripping of cluster members is short enough that the cD envelope can be built up by the collection of *stellar* tidal debris at the bottom of the cluster's potential well (e.g., Richstone 1976; Malumuth & Richstone 1984), accumulating around whatever large galaxy was there initially. Alternatively, the analysis of Merritt (1984, 1985) suggests that in a relaxed cluster with a dominant smoothly distributed background potential, the time scales for dynamical friction and collisional stripping should exceed a Hubble time, and the massive central galaxy actually grows only slowly. Thus if cD envelopes comprise material taken from other galaxies, they must be assembled efficiently before cluster relaxation. More generally, mergers will affect the inner body of a galaxy but are incapable of *forming* the enormously extended envelopes that define the cD phenomenon (Schombert 1987, 1988), and they do not appear to have played a major role in the history of M87 specifically (Malumuth & Kirshner 1981).

Although the size of the corona around M87 is far smaller than in other, much more extreme cD's such as the prototypical NGC 6166 and many others (see Schombert 1986; but see C&D for a different view), it satisfies all the normal criteria for the definition of an envelope, and we consider it to be a true (albeit incipient) cD. The structural similarity of the envelope light and the GCS envelope suggests to us that the origins of the two systems must be related. Thus, we suppose the formation of the envelope to be connected to the stripping of cluster members; the question remaining is one of timing, and it is here that our measurement of β comes into play.

Tidal stripping from galaxies that have already finished star formation will take field stars and globular clusters in the same proportion in which they are found. That is, S_N for any material accreted by M87 this way will be conserved. But now, we find that the main body of M87 and its cD envelope are *both* clearly high-S_N systems while all the other Virgo galaxies are not. Two possible explanations are then that either (1) all the Virgo galaxies formed GCSs with high S_N ($\sim$15–20) but the centrally located M87 was uniquely able to retain them while the other galaxies somehow evolved later toward a low-S_N state; or (2) globular cluster formation was superefficient *only* for M87, which is the only place in Virgo now seen to have a high S_N.

In our view, the first alternative appears too contrived to be considered seriously, since it would require the mechanisms for reducing S_N (e.g., globular cluster destruction; mergers) to operate very efficiently on every galaxy *except* M87, over the full range of morphological types and dynamical histories that we see in the Virgo environment. We are then left with the second scenario, that the M87 region was the only one within Virgo—for physical reasons that are still unknown—in which globular cluster formation happened superefficiently.

That is, the globular clusters throughout M87, both in its main body and in its corona, *were formed in situ* rather than brought in from elsewhere. To account simultaneously for this and for the distinct structure of the cD envelope, it seems necessary to suggest that the envelope was accreted while it was still mostly gaseous, but after the main body of M87 had already gathered. Moreover, it seems most likely that such accretion should occur on a relatively short time scale very soon after any initial star-forming activity in the body of M87, and in particular, before relaxation of the Virgo Cluster.

Finally, it is interesting to consider these results within the larger framework of cD clusters in general. It is becoming clear that not all centrally dominant galaxies in other clusters have high S_N (see Harris, Pritchet, & McClure 1993 and Bridges & Hanes 1993 for a complete list of the known GCSs in cDs). However, it is also true that with only one exception (UGC 9958, the cD in A2107), all the known high-S_N galaxies are located in clusters of Bautz-Morgan class II or III, that is, in clusters with a small magnitude difference between the first- and second-ranked galaxies (Sandage & Hardy 1973). By contrast, low-S_N cDs are found in BM class I or I–II clusters, which have a large luminosity difference between the dominant cD and the second-ranked galaxy and where the cD might have grown more by absorbing large neighbors, thus diluting its globular cluster population (Harris 1981; Pritchet & Harris 1990). In this context, the fact that M87 is a high-S_N galaxy in a BM class III cluster is entirely consistent with the less extreme size of its cD envelope.

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