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THE CORE OF THE M87 GLOBULAR CLUSTER SYSTEM

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ABSTRACT

High-resolution CCD observations have been used to identify 124 globular clusters with $m_B < 23.6$ within 60″ of the center of M87. The luminosity function of these clusters is indistinguishable from that measured further out by other investigators. The core radius r_c of the cluster system is an order of magnitude larger than that of the underlying galaxy surface brightness distribution. The present data combined with those of other investigators imply $r_c = 88'' \pm 5''$ and a central surface density of 72 ± 4 clusters arcmin^{-2} with $m_B < 23.6$. The large core of the cluster system may be a relic of the formation epoch. It appears that dynamical friction cannot produce a core this large from a system as centrally concentrated as the galaxy.

Subject headings: clusters: globular — galaxies: general

I. INTRODUCTION

The unusually rich system of globular clusters around the giant elliptical galaxy M87 presents an excellent opportunity to study the structural relationship between globular cluster systems and their parent galaxies. Cluster systems generally have flatter surface density profiles than their associated galaxies, which may mean that their formation proceeded differently from and perhaps prior to galaxy formation (Harris and Racine 1979; Forte, Strom, and Strom 1981). The clusters in M87 are distributed like the galaxy light at large distances from the nucleus but have a flatter distribution at radii less than 3′ (Harris and Smith 1976; Strom *et al.* 1981; van den Bergh, Pritchet, and Grillmair 1985, hereafter VPG). Strom and collaborators conclude that the clusters are bluer at all radii than the background galaxy light, suggesting that they are metal-poorer and hence older than the halo population. The structure of the globular cluster system therefore contains information about the earliest phases of the formation of the visible parts of galaxies.

The cluster system may also tell us about processes which destroy clusters or alter their distribution. for example, it has been suggested that dynamical friction could cause clusters to spiral into the center and form a nuclear star cluster (Tremaine, Ostriker, and Spitzer 1975). This is of particular interest in M87 because of the well-known nuclear luminosity spike, which may at least partly consist of stars (Dressler 1980).

This *Letter* presents the first measurements of the core of a globular cluster system in an elliptical galaxy. The observations consist of 0″.7 FWHM *V* band CCD images obtained with the Canada-France-Hawaii Telescope (CFHT) as part of a program to study the central structure of elliptical galaxies (Kormendy 1985). The excellent seeing conditions and large dynamic range of the CCD make it possible to detect clusters even in the bright core of the galaxy.

II. OBSERVATIONS AND REDUCTION

a) *Basic Image Reduction*

The observations were obtained with an RCA CCD mounted at the CFHT Cassegrain focus. The useful area of the chip is 316 by 498 pixels. At a scale of 0″.22 pixel^{-1}, this gives a field of 1′.16 by 1′.83. Further properties of the CCD camera are described in Walker *et al.* (1984). M87 was positioned slightly northwest of the chip center; it has complete coverage within 29″ of the nucleus and partial coverage out to 60″ in radius. The long axis of the field runs east-west. Instrumental reduction was carried out at Kitt Peak National Observatory. Further analysis was carried out with VISTA (Lauer, Stover, and Terndrup 1983) on Princeton University Observatory's VAX 11/750. The final image used for analysis is a 600 s exposure composite of one 300 s, two 120 s, and one 60 s exposure images. Cosmic rays were first identified and removed from the individual images. Cosmic-ray hits rarely affected more than single isolated pixels and were readily distinguishable from globulars. The three short-exposure images were shifted by sinc interpolation to match the nucleus centroid of the 300 s exposure. The images were then added together. Low-level deferred charge columns in the composite image were identified and fixed (after subtraction of a smooth galaxy model, as described below) by comparing pixel inten-

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sity medians of neighboring CCD columns. Zero-point calibration was obtained from the photometry survey of Burstein, Marzke, and Condon (1985). It was necessary to use sky levels from images bracketing the M87 exposures, since galaxy light dominates the entire field of view. Sky levels measured before and after the M87 exposures agree well, and uncertainty in the background for M87 is not a major source of error since the total sky level only affects the zero-point by 0.1 mag. For consistency with previous studies, the photometry will be referred to the B band assuming $B - V = 0.80$ for globular clusters (Racine 1968; Ables, Newell, and O'Neill 1974).

b) *Photometry of the Globular Clusters*

The photometry of the globular clusters was carried out in three steps: subtraction of M87 galaxy light, identification of the clusters by a matched detector algorithm, and measurement of their luminosities by point-spread function (PSF) fitting. Proper removal of the M87 galaxy light was essential since the brightness contrast of the clusters was often less than 5%. This was done by subtracting a smooth model constructed directly from the measured light distribution (see Lauer 1985). The effect of the jet on the model was removed by clipping out the jet before measurement of the light profile, subtracting the resulting model from the original image, and then refining the clip based on the residuals. Subtraction of the final model left a smooth, flat image, with clusters readily visible into the core of the galaxy (Fig. 1 [Pl. L1]).

The galaxy-subtracted image was correlated with a matched detector constructed from the PSF to provide the best enhancement of faint stellar images against a noisy background (Castleman 1979). The globulars were identified in the filtered image by a threshold peak finder. Since no bright stars are present in the field, the PSF was constructed from a composite of the three brightest globulars. At the present resolution, globulars are completely stellar in appearance. The PSF has dimensions of 0."78 by 0."62 FWHM. It is slightly elongated due to astigmatism resulting from a leak in the vacuum support system of the CFHT secondary mirror. Luminosities of the clusters were measured using the galaxy-subtracted image and PSF-fitting software developed by Don Terndrup for VISTA. These routines were designed for moderately crowded fields with spatially variable backgrounds. The brightnesses of several neighboring or overlapping clusters can be derived simultaneously, and the background is left as a free parameter to remove any residuals left from the galaxy subtraction.

Several Monte Carlo tests were conducted to test the detection and photometry algorithms. Simulated images were created using the measured PSF and a cluster luminosity function with $d \log N/d \log L = -0.65$, consistent with the VPG luminosity function over the region of interest. The luminosity range extended 2 mag fainter than the present cutoff at $m_B = 23.6$. Two series of tests were run. The first was with noise appropriate to the central 10" of M87 and a surface density of 120 clusters arcmin^{-2} with $m_B < 23.6$. The second simulated conditions between 10" and 20" from the nucleus and used a surface density of 80 clusters arcmin^{-2}. Both tests show that it is easy to find clusters with $m_B < 23.6$ throughout the image; no completeness corrections were applied to the photometry. The major difficulty encountered was that a small number of faint clusters could not be recognized near bright clusters due to moderate crowding at the above densities. The solution was to do the photometry twice; objects identified in the first pass were fitted and subtracted, and the residual image was reprocessed to find faint clusters originally hidden in the wings of brighter ones. The luminosity fit was then reperformed for the entire set of globulars. In practice, this interactive procedure picked up almost all faint clusters lost to blends in the first pass. Tests show that only 2% of the clusters above the cutoff remain undetected.

III. ANALYSIS

The above procedures identified 124 globular clusters with $m_B < 23.6$. The brightest cluster has $m_B = 20.75$. The luminosity function of the clusters and the assumed luminosity function, $d \log N/d \log L = -0.65$, used in the Monte Carlo tests are shown in Figure 2. The luminosity function derived in VPG and scaled to the same total number of clusters with $21.0 < m_B < 23.6$ is also shown for comparison. The present and VPG luminosity functions agree extremely well. The VPG luminosity function was derived from globulars at $r > 60''$ in M87, while the present study just reaches out to this radius. The similarity of the present and VPG luminosity functions is therefore interpreted to mean that there is no obvious physical difference between cluster populations in the center and further out. Further, no significant dependence of cluster luminosity on distance from the nucleus was found. These results constrain mechanisms operating in the dense central regions of M87 which might selectively create or destroy clusters as a function of their masses.

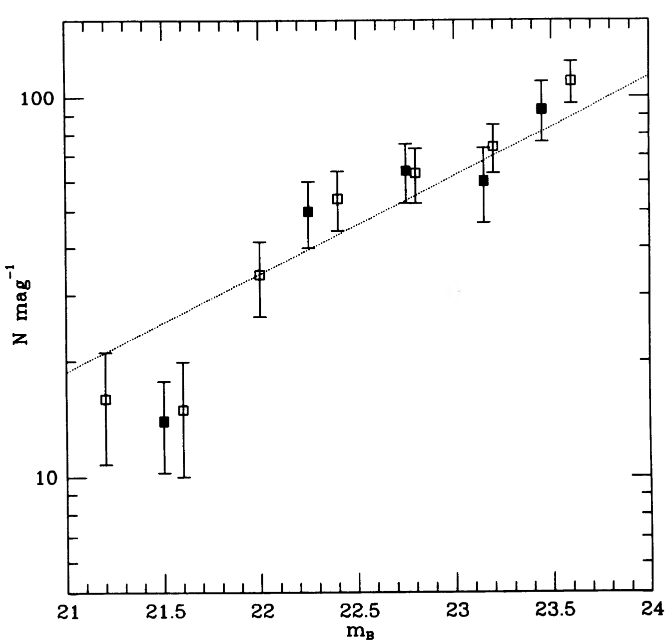

FIG. 2.—Differential luminosity function of the central cluster population (*solid symbols*) compared to the VPG luminosity function normalized to the same number of clusters with $21.0 < m_B < 23.6$ (*open symbols*). The dashed line shows the assumed luminosity function, $d \log N/d \log L = -0.65$, used in the Monte Carlo tests.

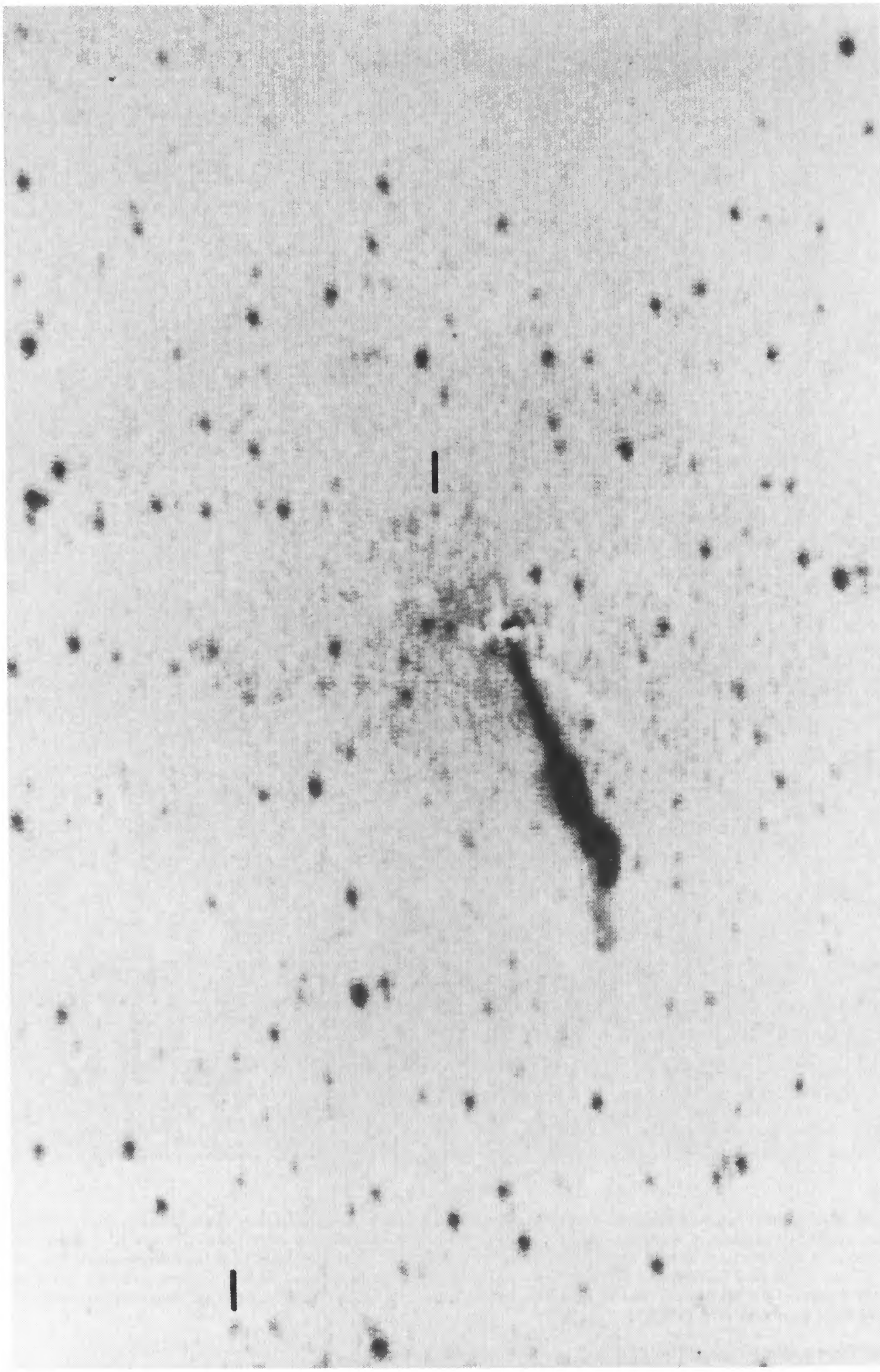

FIG. 1.—Composite *V* band CCD image of M87 with the galaxy light subtracted. The field of view is 70″ by 110″. The galaxy center is at the narrow end of the jet. Tick marks identify two clusters near the luminosity cutoff at $m_B = 23.6$. Note the nearly uniform distribution of globular clusters.

LAUER AND KORMENDY (*see* page L2)

TABLE 1

GLOBULAR CLUSTER COUNTS

Radial Bin	N	Area (arcmin^2)
0″–5″......	3	0.022
5–10	7	0.065
10–15	5	0.109
15–20	13	0.153
20–25	13	0.196
25–30	13	0.238
30–35	18	0.244
35–40	13	0.253
40–45	10	0.227
45–50	12	0.215
50–55	12	0.171
55–60	4	0.054

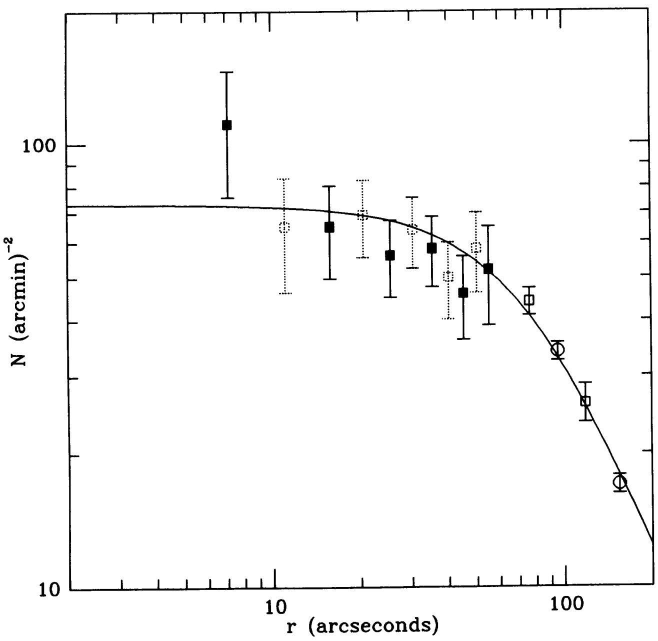

FIG. 3.—Background-corrected surface density of clusters with $m_B <$ 23.6. Present data are shown in 10″ radial bins both starting from the center (*filled squares*), and offset by 5″ (*dashed squares*). Data outside of 60″ are from VPG (*open squares*) and Harris and Smith (1976) (*open circles*). The solid line is a concentration 2.5 King (1966) model fitted to the data.

The observed radial distribution of cluster counts in 5″ bins is presented in Table 1. The area of each bin is also given to allow correction for the partial coverage of M87 outside of the central 29″. The same data converted to surface densities and corrected for background objects are plotted in Figure 3. Bins of 10″ width are used to improve the signal-to-noise ratio for display; the bin centers are at radii which divide the area of the bins in half. Similar points offset by half of a bin width are also plotted to show the effects of binning. The expected background was computed from equation (1) in VPG and is expected to be only four stellar "objects" per square arcminute for $m_B < 23.6$. None of the clusters appeared different from or more extended than the PSF; the present data do not appear to be contaminated by more extended background galaxies.

The most important result of this study is the apparent observation of a core in the M87 globular cluster system. As shown by Figures 1 and 3, the surface density of clusters at $r < 60''$ is nearly uniform, showing only a slight decrease with increasing radius. The core becomes apparent when the present data are combined with surface densities outside of 60″ provided by VPG and by Harris and Smith (1976). (Both papers give densities for $m_B < 23.8$; these were multiplied by 0.84, the ratio of the cumulative VPG luminosity function integrated to 23.6 and 23.8 mag.) A concentration 2.5 King (1966) model fitted to the data weighted inversely by their errors gives the core radius, $r_c = 88'' \pm 5''$ and the central surface density, $\Sigma_0 = 72 \pm 4$ clusters arcmin^{-2}. In physical units, $r_c = 7.4$ kpc, and $\Sigma_0 = 2.8$ cluster kpc^{-2}, using a distance[3] to M87 of 17.4 Mpc. The sharp transition between the core and envelope inherent in a King model fits the profile better than the more gradual transition in a Hubble (1930) law; the core of the system may be isothermal.

The core of the cluster system is strikingly large. With $r_c = 88'' \pm 5''$, it is an order of magnitude larger than that of the galaxy light, $r_c = 6\overset{''}{.}8$ (Kormendy 1985). The cluster system is much less centrally concentrated than the galaxy. This result confirms the suspicions of previous investigators (Harris and Racine 1979; VPG), that the system might have a large core, based on the observation that the system profile is shallower at large radii than the galaxy brightness profile.

It is unlikely that dynamical friction alone could produce such a large core from an initially much more concentrated system. Tremaine (1981) shows that in an isothermal galaxy a cluster on a circular orbit interior to an infall radius r_i, where

$$r_i = 0.95\left[\left(\frac{m}{10^6 M_\odot}\right)\left(\frac{275 \text{ km s}^{-1}}{\sigma}\right) \times\left(\frac{t}{1.3\times10^{10}\text{ yr}}\right)\frac{\ln\Lambda}{7}\right]^{1/2} \text{kpc}, \qquad (1)$$

will spiral into the nucleus by time t. Here σ is the galaxy's velocity dispersion, m is the cluster mass, and $\ln\Lambda$ is the usual Coulomb integral. We evaluate r_i using the velocity dispersion measured at the galaxy core radius (Sargent *et al.* 1978) and an age equal to a Hubble time with $H_0 = 75$ km s^{-1} Mpc^{-1}. The median mass of the present sample of clusters is slightly less than $10^6\ M_\odot$, assuming $M/L_B = 2$. We now need to relate r_i to a predicted core radius produced by dynamical friction. Clusters currently at distance r from the nucleus have spiraled in from distance R, where $R = \sqrt{r^2 + r_i^2}$ (Tremaine, Ostriker, and Spitzer 1975). Continuity gives the current cluster spatial density profile, ρ, in terms of the zero-age profile, ρ_0:

$$\rho(r) = \left[1 + \left(\frac{r_i}{r}\right)^2\right]^{1/2} \rho_0\left[\left(r^2 + r_i^2\right)^{1/2}\right]. \qquad (2)$$

[3]The distance is derived assuming $H_0 = 75$ km s^{-1} Mpc^{-1}, a velocity to Virgo of 1055 km s^{-1} (Huchra, Davis, and Latham 1984), and a Local Group infall velocity of 252 km s^{-1} toward Virgo (van den Bergh 1981).

Equation (2) was used to transform a variety of initial density profiles, some with cores and some with pure power laws extending to $r = 0$. The resulting projected profiles always had cores with $r_c \approx 0.5 r_i$ (r_c is defined here simply as the profile half-power radius). For the parameters used in equation (1), the predicted dynamical friction core is thus 16 times smaller than the observed core radius of the cluster distribution. This implies that the original cluster distribution cannot have been like the galaxy light. This result is strong enough that it is not likely to be affected by the simple approximations used in deriving equation (1).

Dynamical friction will still cause the innermost clusters to spiral into the nucleus, even if it cannot affect the overall structure of the cluster system. The total luminosity of centrally accreted clusters can be calculated using equation (1) and the VPG luminosity function. The predicted luminosity of the central star cluster is $m_V = 20.0$. This is an order of magnitude less luminous than $m_V = 16.9$–17.5 for the observed luminosity spike (Kormendy and Lauer 1985). We note, however, that the predicted m_V is highly sensitive to the approximations inherent in equation (1) and that at least some of the emission from the luminosity spike is nonthermal.

IV. SUMMARY

We have identified 124 globular clusters with $m_B < 23.6$ within 60″ of the M87 nucleus. The luminosity function of these clusters is indistinguishable from that of clusters outside the central 60″. This result constrains mechanisms operating near the center of the galaxy which might selectively destroy or create clusters as a function of their mass. The cluster surface density over the inner 60″ shows little concentration and only a shallow radial gradient. This is strikingly different from the central distribution of galaxy light. A King model fit gives the core radius of the cluster system as $r_c = 88'' \pm 5''$, an order of magnitude larger than $r_c = 6''.8$ for the galaxy.

It does not appear that dynamical friction could have produced a core this large from a system as centrally concentrated as the underlying galaxy. If the large core is a relic of galaxy formation, it may be further evidence that globulars formed before the rest of the galaxy, when the overall mass distribution was less centrally concentrated than it is now (cf. Harris and Racine 1979). However, it is still possible that the cluster system has been modified by processes other than ordinary dynamical friction.

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