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GLOBULAR CLUSTER SYSTEMS IN THE SUPERGIANT ELLIPTICALS OF THE COMA CLUSTER

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ABSTRACT

CCD photometry from the prime focus of the CFHT reveals the existence of globular cluster systems around both of the supergiant elliptical galaxies at the center of the Coma Cluster, NGC 4874 and NGC 4889. Excess populations of images around both galaxies begin to appear in significant numbers near $B = 24.5$, increasing to the limit of the data at $B = 25.7$. Their luminosity function (LF) matches the shape of the Virgo/M87 globular cluster LF for a "normal" assumed distance ratio $d(\text{Coma})/d(\text{Virgo}) = 5.5$.

The cluster population in NGC 4874 is distinctly larger than that in NGC 4889, with a specific frequency S (number of globular clusters per unit galaxy luminosity) almost 3 times higher. In both size and radial structure, the system in NGC 4874 seems to be generally similar to the M87 system, while NGC 4889 more nearly resembles the majority of large ellipticals.

Subject headings: clusters: globular — galaxies: general

I. INTRODUCTION

Investigation of globular cluster systems (GCSs) around the most distant galaxies possible is of interest for two reasons: first, the exploration of these systems is necessary for the eventual use of globular clusters as "standard candles"; and second, the full variety of globular cluster systems in galaxies of all available sizes, types, and environments can be studied only by reaching to distances well beyond the Virgo Cluster.

Since globular clusters are direct fossil remnants of the earliest star-forming epoch in galactic halos, they should be capable of informing us how different (or how similar) this epoch was in galaxies of diverse properties and locations. In this respect, the large ellipticals in the Coma Cluster have long been a challenging and intriguing target: since Coma is the nearest example of an Abell "regular" (extremely rich, centrally condensed) cluster of galaxies (Bautz-Morgan class II, $R = 4$; e.g., Bahcall 1977), it represents an environment unlike anything in or near the local Virgo supercluster. However, the globular clusters in the Coma galaxies are likely to be about 3.7 mag fainter than those in Virgo: their mean radial velocities are $V_0(\text{Virgo}) \approx 1025$ km s^{-1} (Sulentic 1980; Mould, Aaronson, and Huchra 1980; Huchra 1985) and $V_0(\text{Coma}) \approx 6950$ km s^{-1} (Tifft and Gregory 1976; Kent and Gunn 1982; The and White 1986); a correction of ~ 300 km s^{-1} for Local Group motion relative to the Virgo center then gives a distance ratio $d(\text{Coma})/d(\text{Virgo}) = 5.5$. [This estimate may be compared with more nearly direct recent measurements of $d(\text{Coma})/d(\text{Virgo})$ by Dressler 1984, who deduces 5.6–6.3, and Aaronson *et al.* 1986, who deduce 5.5 ± 0.3.] If the brightest globular clusters in M87 (Virgo) appear at $B = 21.0$ (Hanes 1977; van den Bergh, Pritchet, and Grillmair 1985), then in the Coma ellipticals they should resolve at $B \approx 24.7$, with their peak frequency or luminosity function (LF) "turnover" near $B \approx 28.4$. Thus a secure photometric limit in the range $B = 25.5$–26.0 should plainly resolve the GCSs in the largest Coma ellipticals. It should be remembered, however, that such a measurement limit is much harder to reach for crowded images embedded in the bright outskirts of a giant elliptical galaxy than in any typical "blank" high-latitude field.

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II. OBSERVATIONS

On the night of 1986 March 11/12, I took advantage of excellent seeing conditions on Mauna Kea to obtain CCD exposures of the Coma supergiant ellipticals NGC 4874 and 4889. The RCA1 camera at the prime focus of the CFHT was used, with frame dimensions 320×512 pixels and a scale $0''.41$ pixel^{-1}. Short-exposure frames of standard stars showed the intrinsic image sizes to be $0''.6$ FWHM; on long exposures of the program fields, these broadened (through the automatic guider) to $0''.86$ FWHM (NGC 4874) and $0''.94$ (NGC 4889). The final measured frames were the sum of a 6×1200 s B series for NGC 4874 and 3×1200 s for NGC 4889. The B mag calibration was set by direct transfer from equatorial standards (Landolt 1983) and an M67 field (Schild 1983) measured during the night. A more complete description of the data reduction and calibration will be published in the analysis of globular cluster LFs in three Virgo ellipticals obtained in the same observing run (Harris and Allwright 1987).

The CCD photometric reduction code DAOPHOT (Stetson 1987) was used to complete all the analysis of the frames (image finding, point-spread function fitting, and iterative multiple-star fitting solutions for the whole frame). A preliminary step was to remove most of the galaxy envelope light across each frame, by repeated median filtering of the original picture to yield a smoothed picture of just the large-scale light distribution; the R2D2 code (C. Pritchet, private communication) was used for this purpose. (See Harris, Smith, and Myra 1983; Grillmair, Pritchet, and van den Bergh 1986; and Lauer and Kormendy 1986 for other examples of the general technique.) The smoothed picture was then subtracted from the original to leave only the faint, small images on an artificially flattened background. This approach is extremely effective for enhancing the visibility of faint images on the frames, though it fails to remove the very centers of the big galaxies correctly. Figures 1 and 2 (Plates L4 and L5) show the filtered pictures of the two program fields.

Both the NGC 4874 and 4889 fields are complex, with several other Coma galaxies in the frames. During the DAOPHOT reduction, the centers of all the larger galaxies were masked out to prevent false image detections generated by internal noise in these areas. The threshold for image detection, after several preliminary trials, was set at 10 ADU (or $\sim 280\ e^-$) above the sky level, which corresponds to about 4 times the standard deviation of the average background noise across the frame. The background level (sky plus galaxy light) was several hundred ADU near the outskirts of the frames, increasing sharply in the galaxy centers up to a maximum of about 2000 ADU (regions of still higher intensity on the original picture fell within the masked-out nuclei and were not measured). Although the variance of the noise increases toward each galaxy center, the threshold was set high enough to ensure that no significant numbers of "noise" images would contaminate the derived LF. The DAOPHOT image shape parameters SHARP and ROUND were used to eliminate clearly nonstellar images (obvious faint background galaxies or single-pixel defects), but no other image classification was performed. The complementary work of Thompson and Valdes (1987), which investigates a smaller field near NGC 4874 to a somewhat fainter magnitude limit and at higher resolution, contains a more rigorous image separation procedure than was possible here and thus yields a purer sample of the (starlike) globular cluster images. The LF derived in my case depends on *statistical subtraction of a comparison field* from each Coma galaxy field.

The comparison field was a 9×1200 s exposure series taken during the same night of a high-latitude "blank" field well outside the Coma Cluster. The final image size on the summed field frame was 0".81 FWHM, and it was reduced through DAOPHOT in exactly the same way as the Coma fields. Thus in both the Coma and background fields, the derived LFs are a mixture of genuinely starlike images (globular clusters plus foreground field stars) and *slightly* nonstellar ones (small, faint background galaxies). The nonrandom clustering of the latter population from one field to another is the main source of uncertainty in the subtraction of the field LF (see also comments by van den Bergh, Pritchet, and Grillmair 1985).

The final step in the reduction was to estimate the completeness $f(B, r)$ of the photometry, as a function of magnitude and of radius from the center of the galaxy. This was done through DAOPHOT by adding groups of false star images (scaled PSFs) of known magnitudes at random places in the picture, remeasuring the frame, and calculating the fraction that were successfully recovered. The internal errors of the photometry were found to be typically ± 0.05 mag at $B = 23$, increasing to 0.1 mag at $B = 24$ and 0.2 mag at $B = 25$. In the background field, serious incompleteness ($f < 0.8$) does not set in until $B > 26$ since it is quite a "clear" area on dark sky; but for the Coma fields with greater crowding and background light, the photometry starts becom-

TABLE 1

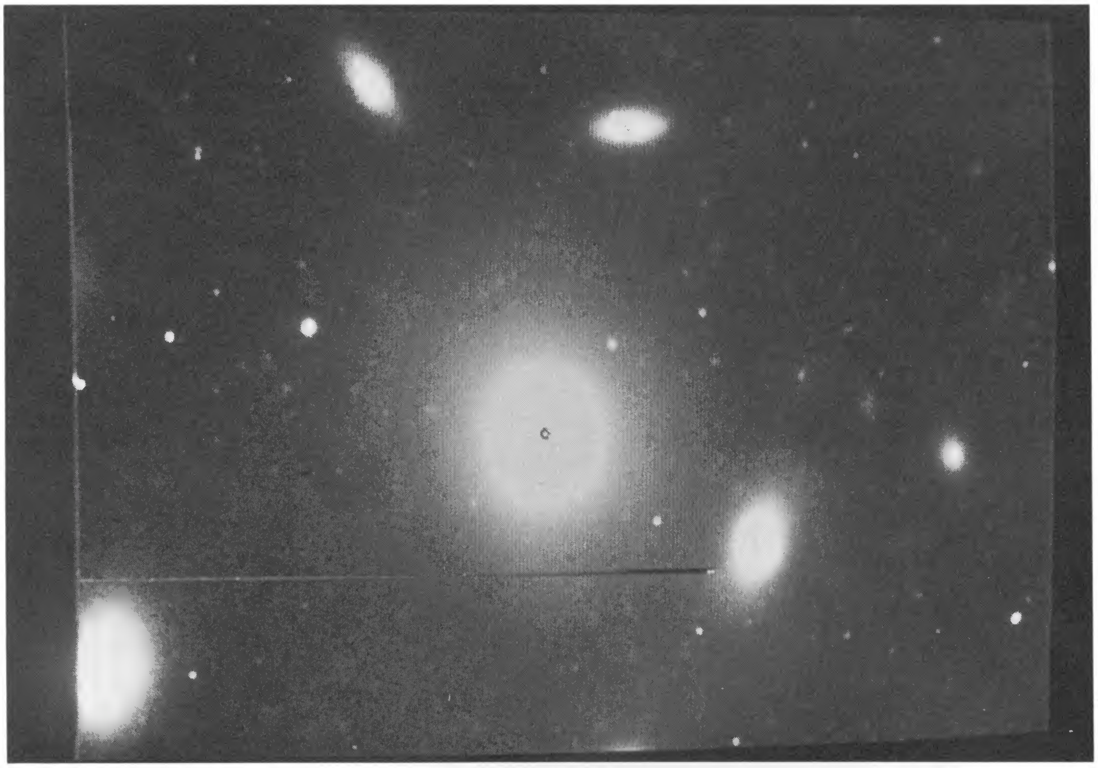
LUMINOSITY FUNCTIONS FOR THE PROGRAM FIELDS

B RANGE (1)	COMPARISON FIELD[a] (2)	NGC 4874[b] Observed (3)	*f* (4)	Net (5)	NGC 4889[c] Observed (6)	*f* (7)	Net (8)
23.00–23.25.......	2	3	1.00	2.0 ± 2.1	3	1.00	2.0 ± 1.8
23.25–23.50.......	2	2	1.00	1.0 ± 1.8	2	1.00	1.0 ± 1.6
23.50–23.75.......	3	8	1.00	6.6 ± 2.9	3	1.00	1.6 ± 1.8
23.75–24.00.......	5	5	1.00	2.6 ± 2.5	4	1.00	1.6 ± 2.2
24.00–24.25.......	5	15	1.00	12.6 ± 4.0	5	1.00	2.6 ± 2.4
24.25–24.50.......	6	19	1.00	16.1 ± 4.5	5	1.00	2.2 ± 2.5
24.50–24.75.......	18	21	1.00	12.4 ± 4.8	18	0.97	10.0 ± 4.8
24.75–25.00.......	20	27	0.98	17.8 ± 5.6	26	0.91	19.1 ± 6.2
25.00–25.25.......	31	51	0.93	40 ± 8	29	0.83	20.2 ± 7.3
25.25–25.50.......	50	52	0.78	42 ± 12	43	0.70	38 ± 13
25.50–25.75.......	66	45	0.4:	86 ± 30:	47	0.4:	76 ± 30:

[a] Area = 7.43 arcmin^2. Completeness fraction $f = 1.0$ for all entries.

[b] Area = 3.52 arcmin^2, centered on the galaxy. Col. (3) gives the number of detected images in the region; f (col. [4]) is the average completeness of detection over the whole area; and col. (5) is the net total after correction for local incompleteness and subtraction of the background LF. The quoted error includes $n(\mathrm{obs})^{1/2}$ for both program and comparison fields, plus the estimated uncertainty in f.

[c] Area = 3.52 arcmin^2, extending from the south edge of the CCD frame (Fig. 2) to an E–W line 1'.27 north of galaxy center (slightly more than halfway to the north edge of the frame).



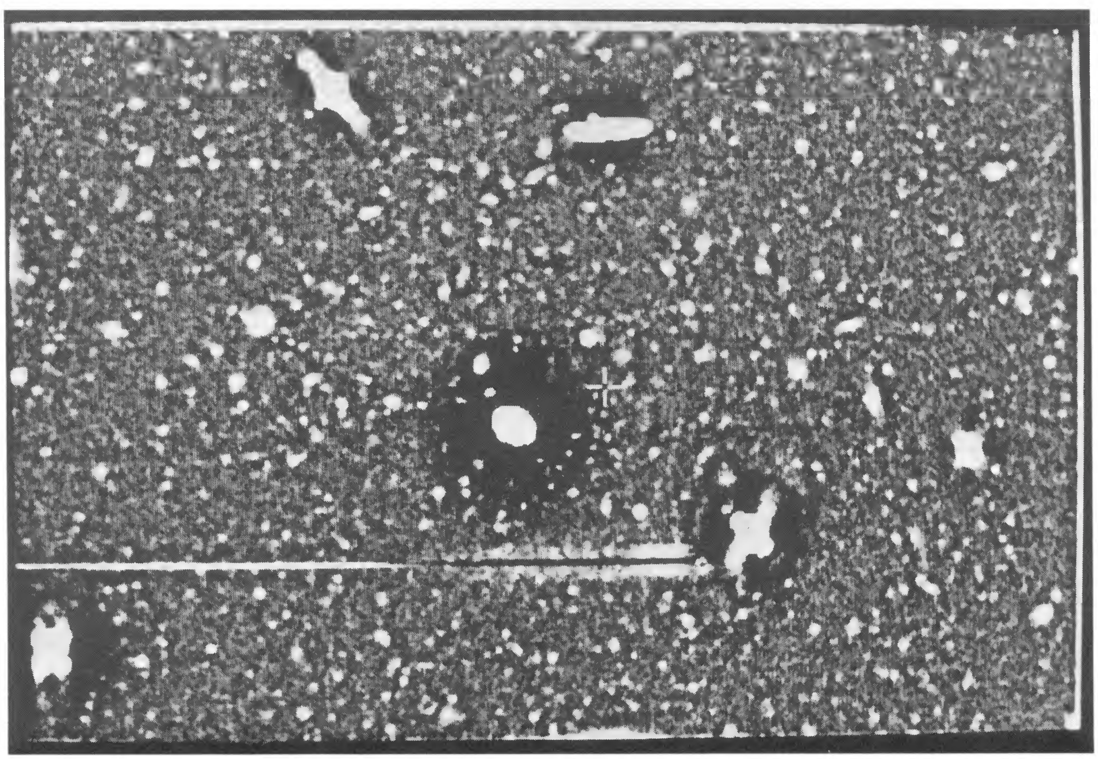


FIG. 1.—The NGC 4874 field, taken with the RCA1 CCD camera at the prime focus of the CFHT. (*top*) A single 1200 s exposure in B; east is at top and north at left. NGC 4874 is the largest galaxy at center. (*bottom*) The final digitally processed image, consisting of the sum of 6×1200 s frames median filtered to remove the galaxy light gradients across the field (see § II of the text). The field size is 2'.1 EW × 3'.4 NS.

HARRIS (*see* page L30)

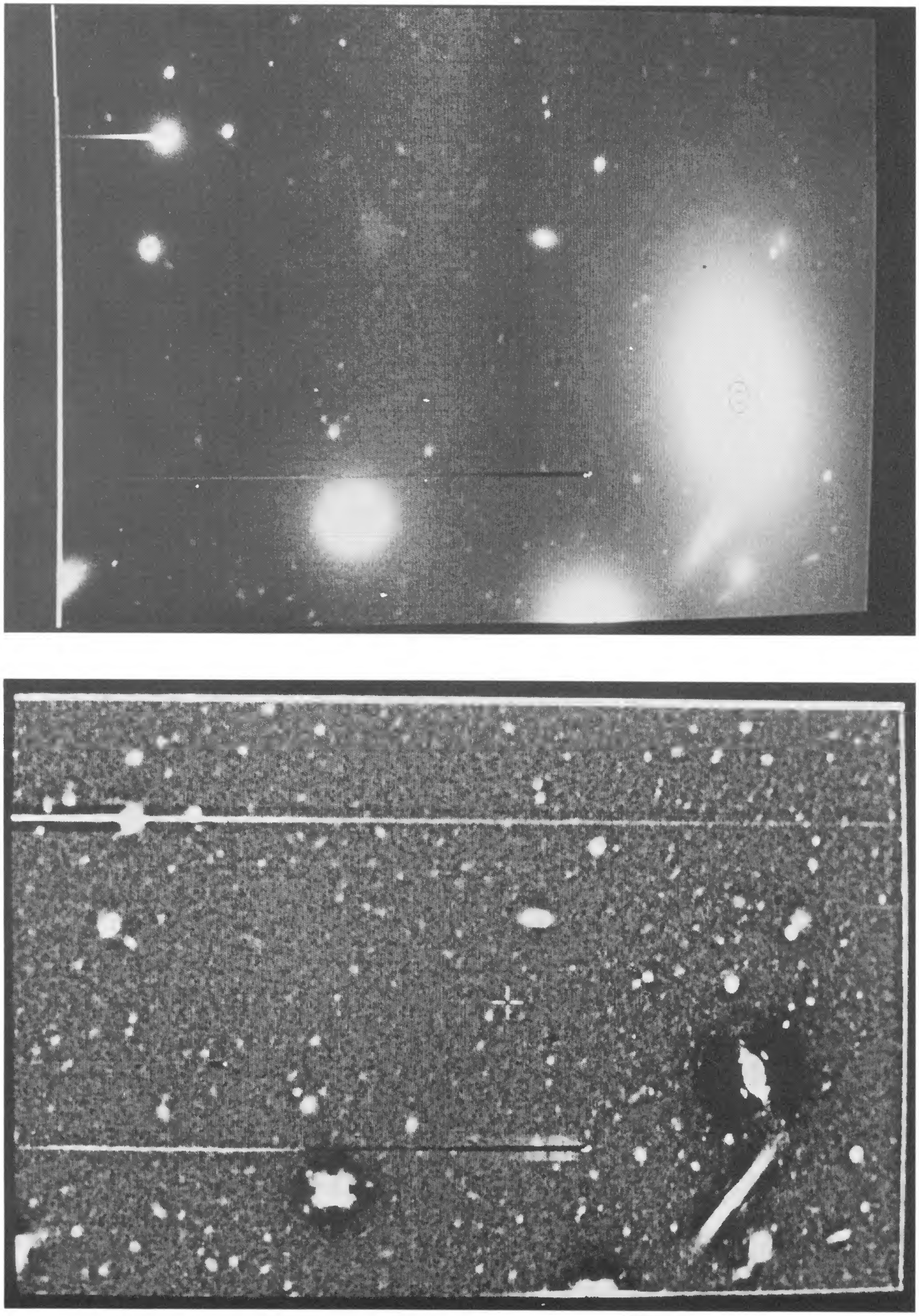


FIG. 2.—The NGC 4889 field, with the same orientation as in Fig. 1. (*top*) A single 1200 s exposure in *B*; NGC 4889 is the largest elliptical at lower right. The frame was positioned off center to avoid a bright star to the south. (*bottom*) The final digitally processed image, a 3 × 1200 s series median filtered as described previously. Note the smaller number of excess faint images in the field compared with NGC 4874.

HARRIS (*see* page L30)

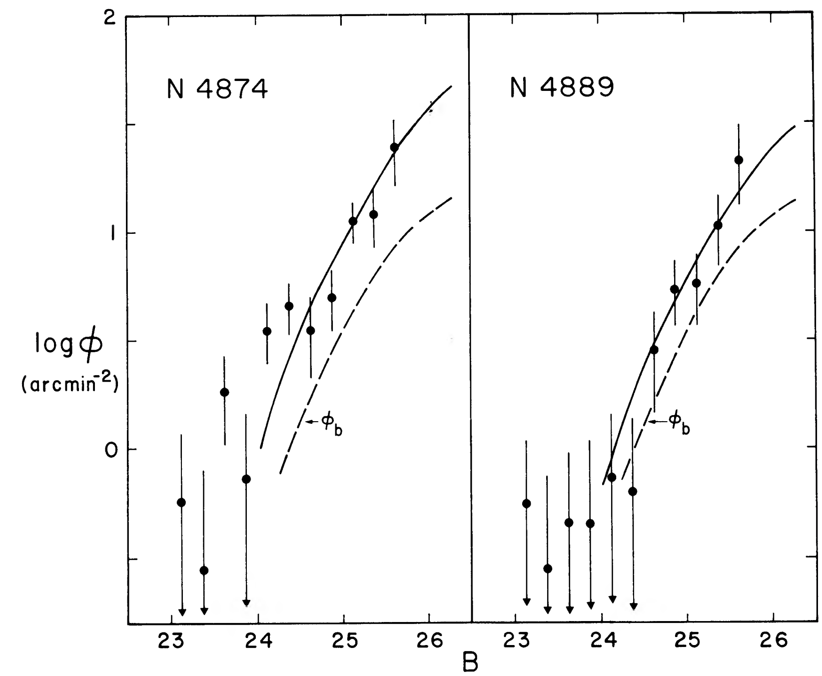


FIG. 3.—Luminosity functions for the excess images around each of the Coma supergiant ellipticals. Here ϕ is the residual number of objects per arcmin^{-2} per quarter-magnitude interval, after subtraction of the comparison-field LF (see § II of the text). The field LF is plotted as the broken line in each panel for comparison. The solid line represents the Virgo/M87 globular cluster LF (Harris 1987), shifted 3.7 mag fainter and then normalized vertically to match the plotted points.

ing incomplete near $B = 25$, with f dropping rapidly to nearly zero at $B = 26$.

III. LUMINOSITY FUNCTIONS AND SPECIFIC FREQUENCIES

In Table 1, the luminosity functions for the three measured fields (NGC 4874, 4889, and comparison field) are summarized. The data for the two galaxies each refer to an area of 74,700 pixels^2 (3.52 arcmin^2) around the galaxy, after exclusion of a central circle of 40 pixels radius (17″) within which the nuclear light prevented useful photometry (for NGC 4889, the area just to the west of the nucleus containing a bright disk galaxy was also excluded). The data for the comparison field are for a larger area of 7.43 arcmin^2 and were divided by 2.11 before subtracting from the Coma fields.

The resulting LFs are plotted in Figure 3. As expected, no significant numbers of excess images are found for $B < 24.0$ (the fact that the net totals in the first four rows of Table 1 are slightly positive may simply mean that the background LF is a bit lower than its "true" local value in Coma; see also § IV below). As seen in the figure, the LFs for both galaxies increase with magnitude in the way expected, under the assumption that they are basically similar to the Virgo/M87 globular cluster LF and that Coma is 3.7 mag more distant than Virgo.

The specific frequencies S (Harris and van den Bergh 1981) of N4874 and N4889 can be evaluated with respect to M87 as follows. For $24.0 < B < 25.5$, there are in total (141 ± 17) excess objects in the measured region around NGC 4874 (Table 1). Of these, I find (121 ± 14) are within a more well-defined complete annulus from 41 to 141 pixels (17″ < r < 58″). If Coma is 5.5 times more distant than Virgo, then this annulus corresponds to a radial range 93″ < r < 320″ around M87; and within that M87 zone there are (1200 ± 50) globular clusters down to B(lim) = 24.2 (Harris 1986). Last, B(lim) = 25.5 at Coma corresponds by assumption to B(lim) = 21.8 at Virgo; and the data of van den Bergh, Pritchet, and Grillmair (1986) show that M87 has (13 ± 3) times as many clusters at $B = 24.2$ as at $B = 21.8$. Thus if M87 were displaced to the Coma distance, we should expect to see (93 ± 20) clusters brighter than $B = 25.5$ and within the N4874 annular zone defined above.

Since the integrated magnitudes of the two galaxies are B_T(M87) = 9.56 and B_T(N4874) = 12.9 (de Vaucouleurs, de Vaucouleurs, and Corwin 1976), M87 is ~ 1.4 times intrinsically fainter than N4874. Normalizing for this difference then suggests that their relative global specific frequencies are S(M87)/S(N4874) = [(93 ± 20)/(121 ± 17)] × 1.4 = 1.1 ± 0.3. Thus within the errors of this rough comparison, N4874 and M87 seem quite similar.

N4889 clearly has a less populous GCS. For $24.0 < B < 25.5$, a total of (92 ± 17) excess objects are listed in Table 1, but this cannot be directly compared with the N4874 total because the measured area around N4889 was not centered on the galaxy. Instead, I redefined two slightly smaller rectangular areas (2.17 arcmin^2) positioned identically on both N4874 and N4889, and recalculated the corrected LFs for these regions. Within these I find N(4874)/N(4889) = (112 ± 14)/(60 ± 12) = 1.9 ± 0.5. Since N4889 has B_T = 12.45, it is ~ 1.5 times more luminous than N4874 itself. Their ratio of specific frequencies is therefore S(4874)/S(4889) = 2.8 ± 0.7.

If S(M87) = 15 (Harris 1986), then the comparisons made above suggest S(N4874) ≈ 14 and S(N4889) ≈ 5. These numbers closely resemble the specific frequencies for M87 and M49 in Virgo: M87 (or N4874) has a cluster population far above average for giant ellipticals, while M49 (or N4889) seems completely normal (Harris 1986); interestingly, it is M49 and N4889 that are each the most luminous galaxy in their clusters, *not* M87 and N4874. Another point of comparison is that both M87 and N4874 are likely to be sitting at or near the dynamic centers of Virgo and Coma: their individual radial velocities differ by < 200 km s^{-1} from their cluster mean (or less than 0.2 σ of the central velocity dispersion); both are at or near the geometric centers of their systems; and both contain prominent nuclear radio sources (M87 = 3C 274, N4874 = 5C 4.85); see, e.g., Riley 1975; Bahcall 1977; Kent and Gunn 1982. The other two known gE's with outstandingly high GCS specific frequencies, namely NGC 1399 in Fornax (Hanes and Harris 1986) and NGC 3311 in Hydra (Harris, Smith, and Myra 1983) are also located at their cluster centers. I suggest the Coma data reinforce the interpretation that a *special central location in a rich environment* somehow stimulated the formation of globular clusters around these giant ellipticals, in about 3 times their normal numbers with respect to the halo stars (Harris 1986, 1987).

IV. RADIAL DISTRIBUTION

The CCD field size used here (2.'1 × 3.'4) is large enough to permit some discussion of the radial distribution of the detected images (this is also a consistency test that the excess population of images actually belongs to the central galaxy!). This will be done here only for N4874, since the detected N4889 population is too small to give meaningful results.

Figure 4 displays the projected number density σ (excess objects arcmin^{-2} in the magnitude range $24.0 < B < 25.5$) for four radial zones: (1) 17″–25″ (for which $\sigma = 40 \pm 15$ arcmin^{-2}); (2) 25″–41″ ($\sigma = 58 \pm 10$); (3) 41″–58″ ($\sigma = 45 \pm 8$); and (4) 75″–115″ ($\sigma = 29 \pm 8$). For $r > 25''$, an overall decrease behaving as $\sigma \approx r^{-1}$ is evident. This is a considerably shallower falloff with radius than the galaxy halo light exhibits over the same region (see Fig. 4), but this result should not necessarily be viewed as unusual. As is also shown in Figure 4, the M87 GCS has a rather similar radial structure in its inner parts, steepening to $\sigma \approx r^{-1.6}$ at larger radii (Harris 1986). Once again, the N4874 GCS seems to resemble the M87 system.

A brief comparison with the Thompson-Valdes (1987) data is in order. In a field 0.7 arcmin^2, centered 42″ off the N4874 nucleus, they find an excess population (relative to a more distant background field) of about 32 objects for $23.75 < B < 25.75$. Over the same magnitude range and normalized to the same area (0.7 arcmin^2), I find ~ 27 excess images. Though my total applies to an average over a much larger radial range than the Thompson-Valdes field, it confirms that no serious disagreements exist.

A more surprising result is that Thompson and Valdes find almost half their excess population (for $B \lesssim 25.5$) to be *nonstellar*. These objects (possibly dwarf satellite galaxies around N4874) turn out to be distributed over magnitude rather uniformly, while the excess starlike images (globular clusters) increase much more steeply with B. Accounting for this result would modify Figure 3*a* and Table 1 such that the residual LF for N4874 would become *steeper* (and hence closer to the shape of the M87 LF, with only the vertical normalization changed). Interpolating between the Thompson-Valdes data, I estimate that a *very rough* correction to my net LF would be to subtract an additional ~ 10 objects per quarter-magnitude bin for $B \gtrsim 24.0$. This correction for the residual nonstellar images is uncertain both because of the area factor (the Thompson-Valdes field is one-fifth the size of mine) and because their radial distribution is unknown. Nevertheless, it would strongly support the conclusion that the N4874 cluster population appears in statistically significant numbers only for $B > 25$. The estimated specific frequency for N4874 would be reduced by ~ 30% with this correction.

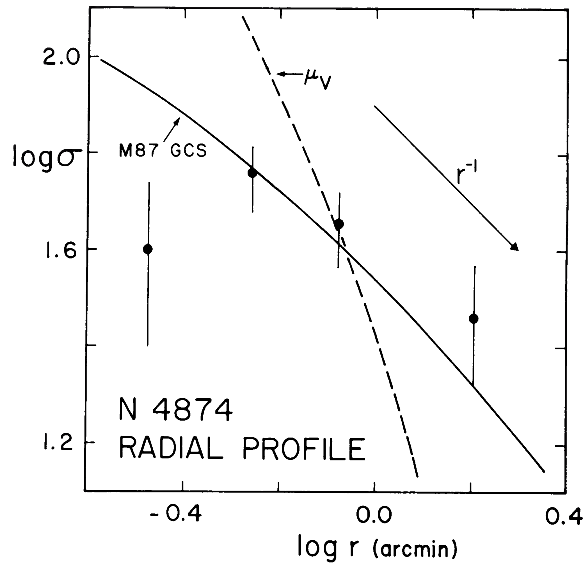


FIG. 4.—Radial distribution of the excess images around the center of NGC 4874. Here σ is the projected image density (objects arcmin^{-2}) for $24.0 < B < 25.5$, for four radial bins as described in § IV of the text. The broken line (μ_v) represents the surface intensity of the N4874 halo light (Rood and Baum 1968), and the solid line is the radial profile of the M87 globular cluster system, normalized to the Coma distance (Harris 1986, 1987; Lauer and Kormendy 1986; Grillmair, Pritchet, and van den Bergh 1986).

Returning to Figure 4, we note that the data point for the innermost ring ($r \approx 20''$, or ~ 10 kpc if Coma is 100 Mpc distant) is especially interesting. Its value is nearly a factor of 2 below what would be expected by analogy with M87. It is doubtful whether this discrepancy can be entirely an artifact of the photometry, since local incompleteness corrections were employed at all points in the frame and the galaxy light is not excessive for $r > 15''$. Furthermore, Thompson and Valdes obtain a rather similar result for $r < 30''$ (see their Fig. 9). Thus there may be a real deficiency of globular clusters in the central region of N4874, extending to 10 kpc or further. Whether the clusters there were systematically destroyed, or never formed there initially, will be a matter for theoretical modeling to address. Dynamical friction for clusters passing through the nucleus has never been shown to be effective over a Hubble time for radii much larger than 2 kpc

(Tremaine, Ostriker, and Spitzer 1975; Lauer and Kormendy 1986; Grillmair, Pritchet, and van den Bergh 1986). Tidal shocking (Ostriker 1987; Chernoff 1987) may be a viable alternative for cluster disruption (or inhibiting their formation?) at larger radii, but simulations appropriate to this case have yet to be carried out.

It is worth stressing that the Coma Cluster is a much richer, denser, and more dynamically evolved environment than any other system in which GCSs have yet been studied. Furthermore, N4874 and N4889 are the most luminous galaxies in which globular clusters have been discovered (Harris 1987). Such a combination of extremes may be connected with the GCS structure in these supergiant ellipticals in ways not yet clearly realized.

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