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A GLOBULAR CLUSTER SYSTEM SURROUNDING THE cD GALAXY NGC 6166

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ABSTRACT

Deep, subarcsecond CCD imaging with the Canada-France-Hawaii Telescope has revealed the existence of a globular cluster population around the cD galaxy NGC 6166 (the central supergiant in Abell 2199, redshift $\simeq 9000$ km s^{-1}). The brightest globulars appear at $B \simeq 25.2$, and increase in number toward fainter magnitudes exactly as would be expected if they were intrinsically similar to those in the Virgo cluster ellipticals. The estimated specific frequency of the system is $S \leq 4$—i.e., at the "normal" level for giant ellipticals rather than at the $S \simeq 15$ level characteristic of M87 and other central supergiant ellipticals studied to date. This result is consistent with the view that cD galaxies form from mergers, but argues against the formation of populous globular cluster systems from cooling flows. A population of dwarf galaxies is also identified around NGC 6166; the number density of these dwarfs is roughly consistent with that of dwarfs around the central Virgo elliptical M87.

Subject headings: clusters: globular — galaxies: evolution — galaxies: individual (NGC 6166) — galaxies: interactions

I. INTRODUCTION

The most populous known globular cluster systems are found around supergiant elliptical galaxies at the centers of rich clusters of galaxies. M87 in the Virgo cluster is the prototype of this class of anomalously rich cluster system (e.g., Harris 1986); others currently known include NGC 3311 in the Hydra cluster (Harris 1986), NGC 1399 in Fornax (Hanes and Harris 1986), and (perhaps) NGC 4874 in Coma (Harris 1987; Thompson and Valdes 1987). These systems share two features that have been found nowhere else. (1) Each has a globular cluster population with a specific frequency $S \gtrsim 15$ (where S is defined as the number of globulars per $M_v = -15$ of luminosity). This S value is about three times the normal value for large ellipticals. (2) Each is sitting essentially *at the dynamical center* of a rich group of galaxies (see Harris 1988*a* for a review).

The origin of these populous globular cluster systems is not well understood. Dynamical exchanges with surrounding galaxies cannot boost the specific frequency, since S is a *number ratio* of clusters to halo field stars; nor can mergers, unless these occur at such an early stage that the (gas-rich) merging fragments can stimulate additional cluster formation (cf., Harris 1986, 1988*a*; Muzzio 1988). An alternative idea (Fabian, Nulsen, and Canizares 1984) is that globular clusters may form continuously from cooling flows; such cooling flows must be common in central gE galaxies because these galaxies are found to possess extended halos of hot, X-ray emitting gas.

In order to better understand the origin of populous, high-S globular cluster systems, we have obtained observations of NGC 6166, the supergiant central cD in Abell 2199, at the front edge of the Hercules Supercluster (Chincarini, Rood, and Thompson 1981). NGC 6166 is a bona fide cD; its very high luminosity, central location in a rich cluster, and large size all suggest that it may be a structure built up by numerous mergers (Dressler 1984; Lauer 1986; but see Merritt 1985 for a different view). Furthermore, it possesses an X-ray halo and deduced cooling flow much higher than for M87 (Fabian *et al.* 1984); this, coupled with possible low-level star formation inferred from UV observations by Bertola *et al.* (1986), suggests that S might be very high if the Fabian *et al.* mechanism were at work. Thus NGC 6166 provides a test case for globular cluster formation scenarios that is quite different from the environments sampled previously.

The brightest clusters in the Virgo ellipticals appear at $B \simeq 21.0$ (Harris 1988*b*), and since A2199 is $\simeq 4.2$ mag more distant (see § IV), we would expect the globular clusters in NGC 6166 to begin to appear at $B \simeq 25.2$. Although faint, this level is well within reach of telescopes enjoying the best ground-based imaging conditions (Harris 1987, 1988*b*; Thompson and Valdes 1987). A 1 hr CCD exposure by Pritchet and van den Bergh (1986, unpublished data) in fact confirmed the presence of a population of faint objects in the envelope of NGC 6166, although the objects were too faint to obtain photometry.

II. OBSERVATIONS AND DATA REDUCTION

The observations on which this paper was based were acquired on the nights of 1988 May 15 and 16 (UT) with the Canada-France-Hawaii 3.6 m telescope. The observations consisted of six 1800 s exposures through a B filter using the RCA4 detector (a cooled RCA SID 006EX007 CCD, 640 × 1024 format, 15 μm = 0".21 pixels, read noise 62e^- pixel^{-1}—see Waddell and Christian 1987; Christian 1988) at prime focus. The seeing for the exposures ranged from 0".73 to 1".00, with a median of 0".85. Preprocessing consisted of the usual (1) subtraction of floating bias level (mean of overclocked pixels), (2) subtraction of mean bias frame, and (3) division by a mean dome flat. Dark current was negligible.

After preprocessing, the following operations were performed. (1) The six individual exposures were aligned and photometrically normalized. (2) Differences were taken

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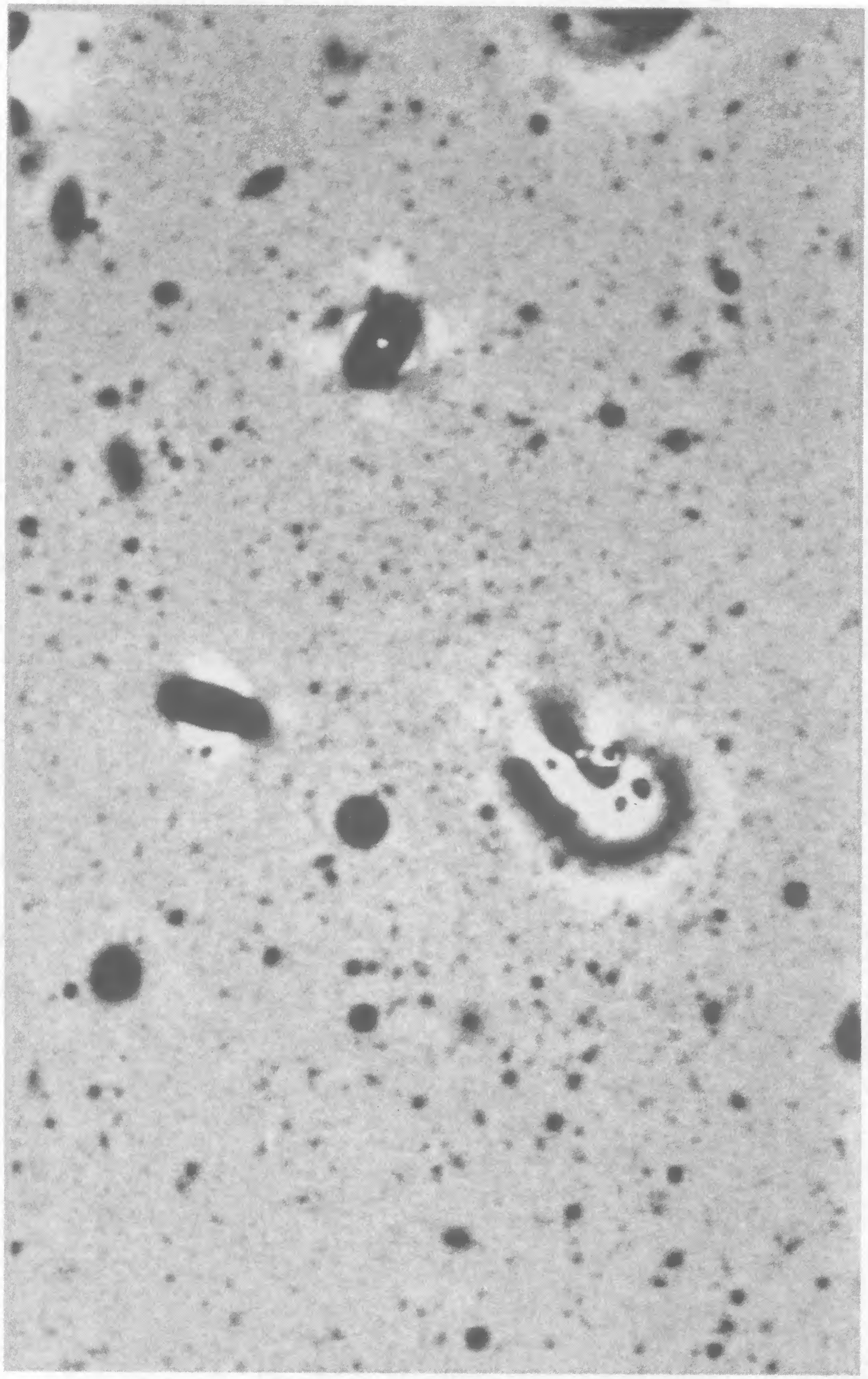

FIG. 1.—Composite image in B of the 2.2 × 3.3 arcmin NGC 6166 field. This is the sum of six 30 minute CCD exposures at the CFHT prime focus, with mean seeing of 0".85. North is at the bottom, and east is to the right. The picture has been median filtered (*see text*) to remove the main portions of the large galaxies in the field and to allow the faint objects surrounding NGC 6166 (*at center*) to stand out more clearly.

between the exposures, and these difference frames were themselves heavily smoothed and filtered, and added back to the individual frames. This operation removed small frame-to-frame normalization and flat-fielding problems that might have otherwise heavily biased the ensuing median operation. (3) A pixel-by-pixel median was taken of all frames. (4) A "background" frame was created to model the distribution of light in the envelope of NGC 6166. This background light was based on the Lauer (1986) photometric decomposition of NGC 6166. (5) The background light model was subtracted from the median frame.

Figure 1 shows the final composite image of the NGC 6166 field, after removal of the background-light frame. It is clear from this picture that an excess population of faint images has been resolved in the vicinity of the central galaxy.

Finding and photometry of objects in the composite frame was done using a modified version of the program DAOPHOT (Stetson 1987). The modifications to this program were of two kinds. (1) Since background light levels had been previously subtracted from the original picture, it was necessary to correct for this fact in the calculation of the noise level at each pixel. (2) The Kron (1980) r_{-2} classifier was calculated for each image, and was used to discriminate between stars and galaxies.

Calibration of the data was performed using large-aperture photometry of bright images on one of the 1800 s exposures. The photometric zero point and extinction coefficient were measured from short exposures of Landolt (1973) standard star fields taken during the night. The transformation of instrumental b into B was taken to be $B = b + 0.20(B-V) +$ const after correction for extinction, following Christian (1988). A uniform color $(B-V) = 0.8 \pm 0.2$ was assumed for all images in the frame; this color is appropriate for globular clusters with a slight amount of foreground reddening (Reed, Hesser, and Shawl 1988). The internal uncertainties in the zero point and color terms together imply that the final B magnitude scale should match the standard system to within ± 0.05 mag.

Completeness of the final data was evaluated by adding artificial stars (scaled point-spread functions) back to the original data, and repeating the DAOPHOT finding and photometry procedure in its entirety. The results of the completeness tests are shown in Table 1. A total of 400 artificial stars were added, 20 at a time, at each magnitude level; the quoted errors in the completeness were calculated from the standard deviation of a binomial distribution. Also shown are the uncertainties (rms scatter) in the recovered magnitudes; the magnitude *scale* error $(m_{\rm DAO} - m_{\rm true})$ is negligible for $B < 26.4$, fainter than which completeness is well below 50%. In principle completeness should vary with radial distance from the nucleus of NGC 6166; however, over the range of surface brightness we studied, no significant radial change in completeness was found.

TABLE 1

COMPLETENESS AND ERRORS

B	f[a]	rms[b]
22.4	0.994 ± 0.006	± 0.008
22.9	0.963 ± 0.015	± 0.011
23.4	0.994 ± 0.006	± 0.019
23.9	0.959 ± 0.015	± 0.028
24.4	0.958 ± 0.016	± 0.051
24.9	0.948 ± 0.017	± 0.080
25.4	0.855 ± 0.022	± 0.106
25.9	0.664 ± 0.030	± 0.205
26.4	0.339 ± 0.027	± 0.272
26.9	0.150 ± 0.019	± 0.317

[a] Completeness fraction (errors from binomial distribution).

[b] RMS uncertainty in recovered magnitude.

We divided the frame into two measured regions, defined according to the intensity of background light at the position of each image. The "inner" zone was defined to be 1.99 arcmin^2 in area, with a mean distance from the center of NGC 6166 $\langle r \rangle = 35''$ [corresponding to $22.55 \leq \mu_B$ (mag arcsec^{-2}) ≤ 24.43, or $17'' < r^* < 41$, where r^* is the effective radius $(ab)^{1/2}$]. The outer or "background" zone was 4.12 arcmin^2 in area, with $\langle r \rangle = 79''$ ($\mu_B > 24.87$ mag arcsec^{-2}, $r^* > 55''$). For the purpose of statistical subtraction of the background luminosity function, we assumed all objects in the outer zone to be foreground and background objects not associated with NGC 6166 (*see below*).

III. IMAGE ANALYSIS

Globular clusters are completely star-like in appearance at the distance of NGC 6166, so an extremely helpful step in

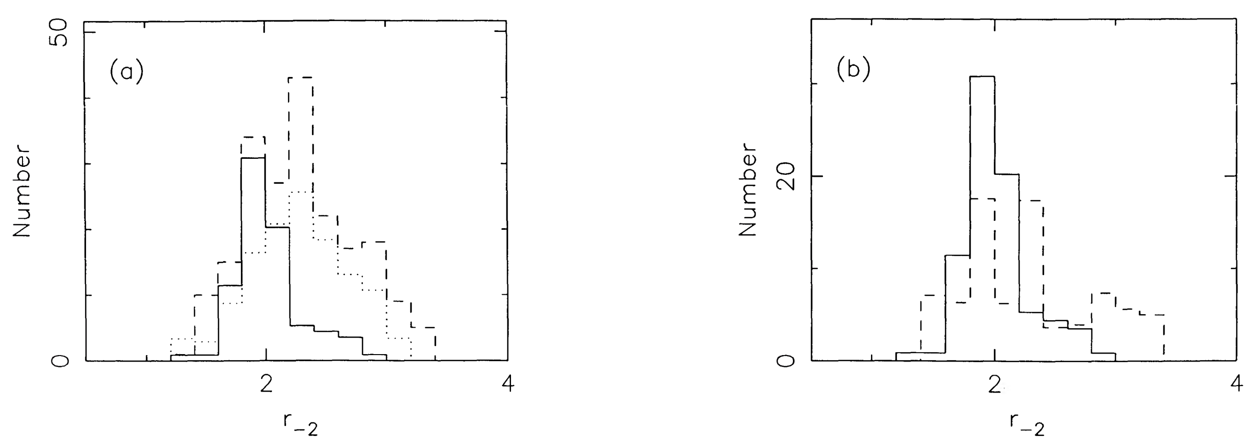

FIG. 2.—Distribution of the Kron r_{-2} image classifier for objects fainter than $B = 25.2$. In both figures, the *solid line* shows the distribution of stellar r_{-2} indices at $B = 25.9$ as computed in DAOPHOT ADDSTAR experiments. (*a*) Distribution of r_{-2} in the inner field (*dashed line*) and outer field (*dotted line*). The number of objects in the outer field has been scaled by 0.483 to match the area of the inner field. (*b*) Inner field minus (*scaled*) outer field (*dashed line*). About one-half of the objects with $r_{-2} > 3$ are spurious, but almost all of the objects below this limit are real.

removing contaminating objects is to apply an objective image classifier (e.g., Thompson and Valdes 1987). To remove probable nonstellar images, we analyzed the distribution of r_{-2} indices for faint objects ($25.2 < B < 26.4$—a magnitude range to be justified later). Here r_{-2} was measured within a (constant) aperture of 6 pixels (1".3) and thus has the same mean value for starlike images at all magnitudes. The solid line in Figure 2 shows the distribution of r_{-2} indices for *artificial stars* added at $B \simeq 25.9$. The median r_{-2} is seen to be 1.9 pixels, and most (~90%) of these artificial stars possess $r_{-2} \leq 2.4$ pixels.

The actual distribution of the real objects found on the frame (dotted and dashed lines in Fig. 2*a*) in both the inner and outer zones is significantly different from that for a population of purely starlike objects. (The distribution of r_{-2} broadens at fainter B; however, the mean B of stars in the magnitude range 25.2–26.4 is ~25.7, slightly brighter than that of the added stars in Fig. 2*a*.) Fig. 2*a* also demonstrates that the surface density of objects in the inner zone is systematically larger than that in the outer zone.

The result of subtracting the observed number of objects in the outer zone (scaled to an area of 1.99 arcmin^2) from the number of objects in the inner zone is shown in Fig. 2*b*. Roughly 50% of the "excess" images in the inner zone are nonstellar, and therefore not likely to be globular clusters. Inspection of individual objects shows that about one-half of the objects with $r_{-2} \geq 3.0$ are spurious multiple hits on very bright galaxies; however, almost *all* of the images below this limit are found to be real. Restricting attention to those objects with $r_{-2} \leq 3$, Monte Carlo simulations show that the probability of the two distributions in Fig. 2*b* being drawn from the same parent population is <5%. The fact that the residual distribution appears to be bimodal rather than rising smoothly from large to small r_{-2} suggests that the objects at larger r_{-2} are a distinct population. The median value for the nonstellar objects, $r_{-2} \simeq 2.6$ pixels, corresponds to a FWHM of 1".2 or ~0.7 kpc at the distance of NGC 6166 (~0.3 kpc after removing the effects of seeing). This is comparable to the diameter of low-luminosity ($M_v \simeq -10$) dwarf galaxies (e.g., Kormendy 1985). *In our residual luminosity function, therefore, a fraction in the range 0.2–0.5 of the "clustered" component of objects surrounding NGC 6166 might be dwarf galaxies*, similar to a result found for the Coma gE NGC 4874 by Thompson and Valdes (1987).

Table 2 gives the raw numbers of *starlike* ($r_{-2} < 2.4$) images in each zone, and their (incompleteness-corrected) numbers per unit area. The last column of Table 2 presents the difference in surface density of the inner and outer zones as a function of blue magnitude. All these data are plotted in Figure 3*a* and 3*b*, where the higher density of images in the inner zone is graphically visible. The excess appears to set in at $B \geq 25.2 \pm 0.2$; this result is not changed if *all* objects are included in the calculation of surface density (rather than just unresolved objects). The level at which the residual luminosity function (LF) "turns on" is exactly consistent with our original expectation (§ I above), and we therefore identify the detected objects as the brightest globular clusters in NGC 6166.

The data are too fragmentary, and cover too narrow a range in radius, to be able to examine in detail the radial distribution of images. A hard lower limit on the power-law exponent β characterizing the radial gradient in object density (where $\sigma \propto r^{-\beta}$) may be obtained by assuming that *all* of the images in the outer zone belong to NGC 6166. With this assumption, one obtains $\beta > 0.6$. For globular cluster systems around other giant ellipticals, β lies in the range $\simeq$1.2–1.7 (Harris 1986).

The surface density as a function of position angle is plotted in Figure 4 for stellar objects. Recall that the inner zone was defined by contours of equal background surface brightness; *if* contours of constant globular cluster density were distributed with the same flattening and orientation as the background light, then the distribution of position angles in Figure 4 would be flat. A χ^2 test indicates that the distribution of points in Figure 4 differs from a uniform distribution only at the ~30% level—i.e., our data are consistent with the globular cluster surface density contours and background light contours being the same to within their uncertainties.

IV. DISCUSSION

The specific frequency S for NGC 6166 is of primary interest. The fact that we see only the top ~1.5 mag of the globular cluster luminosity function (GCLF) means that we can evaluate the total cluster population only by a large extrapolation; nevertheless, the difference between the "high-S" systems like

TABLE 2

LUMINOSITY FUNCTION FOR STELLAR OBJECTS NEAR NGC 6166

		Outer Region			Inner Region		
B	f[a]	N_{raw}[b]	σ_o[c]	σ_o[d] (fit)	N_{raw}[e]	σ_I^c	$\sigma_I-\sigma_O$
22.0–22.4	1.000	0	0	0.07	0	0	...
22.4–22.8	0.974	1	0.24 ± 0.24	0.13	0	0	...
22.8–23.2	0.959	2	0.51 ± 0.36	0.24	1	0.52 ± 0.52	0.3 ± 0.6
23.2–23.6	0.978	0	0	0.43	0	0	...
23.6–24.0	0.960	3	0.75 ± 0.44	0.79	1	0.52 ± 0.52	...
24.0–24.4	0.951	5	1.3 ± 0.6	1.4	3	1.6 ± 0.9	0.2 ± 1.2
24.4–24.8	0.946	9	2.3 ± 0.8	2.6	5	2.7 ± 1.2	0.1 ± 1.6
24.8–25.2	0.924	17	4.5 ± 1.1	4.7	9	4.9 ± 1.6	0.2 ± 2.3
25.2–25.6	0.847	34	9.7 ± 1.7	8.6	22	13.0 ± 2.8	4.4 ± 3.5
25.6–26.0	0.690	46	16.2 ± 2.4	15.6	39	28.4 ± 4.6	12.8 ± 5.3
26.0–26.4	0.455	50	26.7 ± 3.8	28.4	44	48.5 ± 7.3	20.2 ± 8.2
26.4–26.8	0.255	63	60.0 ± 7.6	51.5	47	92.5 ± 13.5	41.0 ± 14.4

[a] Completeness fraction.
[b] Area = 4.12 arcmin^2, $\langle r \rangle$ = 79".
[c] Surface density (per arcmin^2), corrected for incompleteness.
[d] Least-squares fit to background counts; see text.
[e] Area = 1.99 arcmin^2, $\langle r \rangle$ = 35".

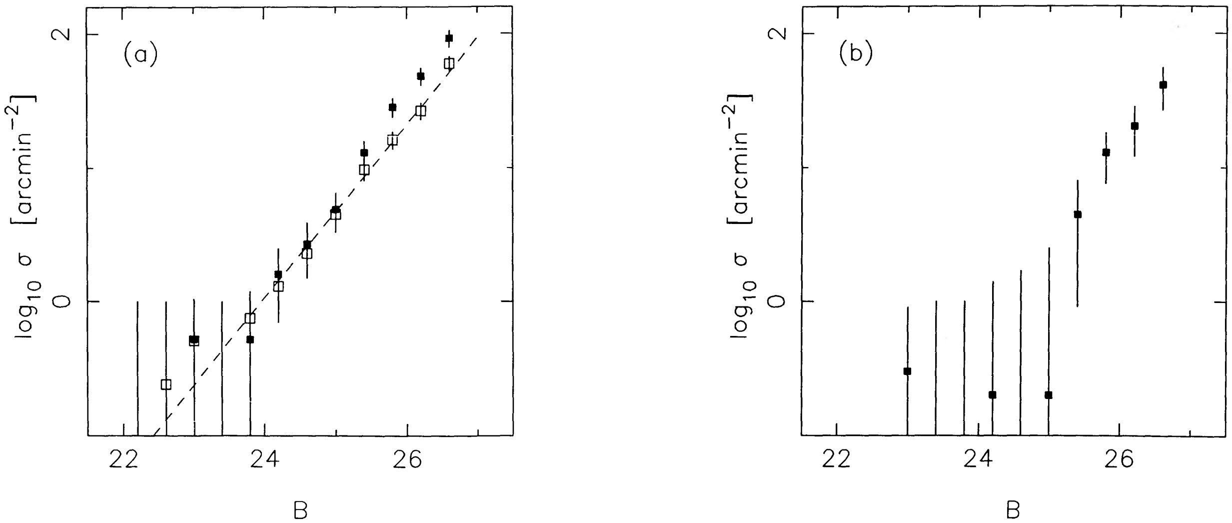

FIG. 3.—Surface density of stellar images ($r_{-2} < 2.3$) in our NGC 6166 field, plotted against B magnitude. All surface densities have been corrected for incompleteness. (*a*) Raw surface densities in the inner (*solid squares*) and outer (*open squares*) areas. The dashed line is a weighted least-squares fit to the surface densities in the outer field. (*b*) Difference between the surface densities in the inner field and the mean (*smoothed curve*) surface densities in the outer field. This graph represents the luminosity distribution of the globular clusters around NGC 6166.

M87 and the normal E's is large enough (cf., $S \sim$ 15–20 vs. ~ 5) that it is possible to distinguish to which category NGC 6166 belongs.

To estimate S, we scale directly from the GCLF for the Virgo E's (Harris 1988*b*); this step *assumes* (1) that the GCLF for NGC 6166 is intrinsically similar to that for Virgo gE's and (2) that the distance of NGC 6166 *relative to Virgo* is given correctly by the ratio of Hubble redshifts (corrected for Virgocentric infall). We believe assumption (1) *not* to be particularly risky, since all the galaxies involved are giant ellipticals. Assumption (2) gives $V_0(\text{A2199})/V_0(\text{Virgo}) \simeq 6.9 \pm 0.6$ if $V_0(\text{Virgo}) = (1300 \pm 100)$ km s^{-1} after correction for Local Group infall (e.g., Huchra 1988); this corresponds to a difference in distance modulus of $\Delta(m - M)_0 \simeq 4.2 \pm 0.2$. In Virgo, the GCLF turnover is at $B = 24.7 \pm 0.15$ and the dispersion of the Gaussian-like LF is $\sigma = 1.4$ mag (Harris 1988*b*; Grillmair, Pritchet, and van den Bergh 1986). In NGC 6166 we observe $N_{\rm obs} = 156 \pm 35$ excess starlike objects (Table 2) to $B_{\rm lim} = 26.8$, a limit which is then equivalent to $B = 22.6 \pm 0.2$ at Virgo, or (1.5 ± 0.2) σ short of the turnover point. This scaling implies that we see only a fraction $\simeq 1/(15 \pm 6)$ of the clusters integrated over all magnitudes, so that in our observed inner zone the predicted true total is $N_t = 2340 \pm 1080$ clusters. Now summing over the isophotal contours, we find that the total light of the galaxy over the same zone adds up to $B_t = 14.00$ mag, or $M_V(\text{equiv}) = -22.46$ for $H_0 = 75$ and $(B-V)_{\rm halo} \simeq 1.0$ (de Vaucouleurs, de Vaucouleurs, and Corwin 1976 [RC2]). The specific frequency is then $S = N_t \times 10^{0.4(M_V+15)} = 2.4 \pm 1.1$, not accounting for uncertainties in the distance scale. Using $H_0 = 60$ rather than 75 in the above calculation decreases S by 40%. If a Gaussian GCLF with $\sigma = 1.2$ (rather than 1.4) is assumed, then S is increased by $\sim 50\%$. If S is calculated using the counts of objects brighter than $B = 26.4$ (rather than 26.8), then S is decreased by 15%.

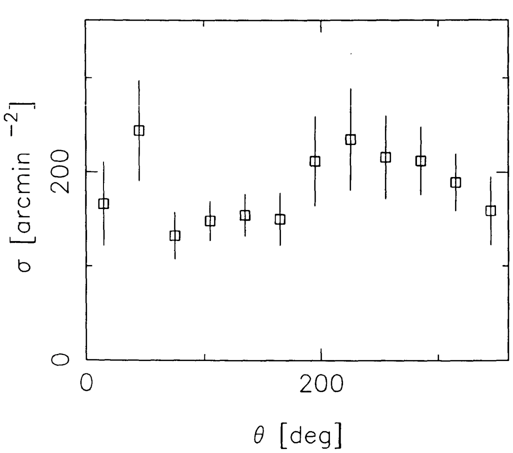

FIG. 4.—Distribution of surface density of stellar images by position angle around NGC 6166, in 30° zones. All images are within an elliptical annulus defined by two contours of equal background intensity in the galaxy.

It is important to note, however, that this calculated S applies only to the measured inner zone. There are three types of corrections to be applied before we can quote a *global* S for the entire galaxy:

1. If the globular clusters have a more extended radial distribution than the galaxy halo light (as is the case for other giant E's; Harris 1986, 1988*a*), then S for any local radial zone must be corrected for the spatial distribution over the entire halo. We cannot evaluate this factor accurately, since (see above) we do not sample a wide enough region to know the radial exponent $\beta(\text{halo}) - \beta(\text{clusters})$. If we again use the Virgo E's as a template and scale from the equivalent radial zone around M87 (Harris 1986), we find $S(\text{global})/S(\text{local}) \simeq 1.8$. Contrarily, if the cD-like structure of NGC 6166 means that the globular cluster system has evolved to the same radial structure as the halo (cf. Harris, Smith, and Myra 1983), then $S(\text{global})/S(\text{local}) \sim 1$.

2. The outer region we employed to define the background will itself contain some globular clusters because it is not a true far-field background with respect to NGC 6166 (we would need $r \gtrsim 200$ kpc or $\gtrsim 5'$ to have a reasonable guarantee of nearly pure background). Again referring to the Virgo radial distributions (Harris 1986), we find that the residual LF for our inner zone should be multiplied by ~ 1.6 for this effect.

3. Some fraction of the residual objects are detectably nonstellar and thus should be rejected from the totals (see above).

Combining all these factors, we estimate $S(\text{global}) \leq 3.5$ for NGC 6166, with an uncertainty of roughly a factor of 2. This result is very near the *normal* value for large ellipticals (Harris 1988*a*), but far below the four anomalously populous giants mentioned above. The principal conclusion of this study is then that *NGC 6166 appears to be the first clear case of a central supergiant galaxy in a rich cluster which does not have the high-S anomaly.* If NGC 6166 possessed as high a cluster specific frequency as M87, then the number of observed clusters would have been ≥ 5 times the number actually detected!

It may not be an accident that NGC 6166 is also the most luminous and has the strongest cD-type structure of the central galaxies sampled so far. Evidence that cD galaxies form from mergers has been compiled by many authors (e.g., Gunn and Tinsley 1976; Ostriker and Hausman 1977; Malumuth and Richstone 1984; Tonry 1987; Bothun and Schombert 1988; but see Merritt 1985 and Tremaine 1990 for a conflicting view). The near-normal S of NGC 6166 is consistent with the idea that it built up its present huge structure by an extended series of mergers with other large galaxies in its neighborhood. For example, it may simply have begun as a rather normal giant elliptical, merged with other E/S0's with similar specific frequencies, and gradually settled to the center of its surroundings if it was not there originally. Because normal E/S0 galaxies have rather similar specific frequencies (Harris 1988*a*) and S is essentially the *ratio* of clusters to field halo stars, it will remain relatively unchanged by the merger process. Alternatively, if it began already at or near the center of A2199, and *if* such galaxies all start out with anomalously high globular cluster populations, then it may have accreted several disk-type galaxies (which have negligible numbers of clusters by comparison) and thus diluted its original cluster population relative to the accumulated total halo light (see Harris 1981, 1988*a*; van den Bergh 1984, 1990 for further comments in this area).

Our observations of NGC 6166 argue clearly against the hypothesis that globular clusters in central supergiant galaxies form continuously out of cooling flows (Fabian *et al.* 1984), and that their excess numbers are due principally to this effect. In NGC 6166 the deduced mass condensation rate from the cooling flow is an order of magnitude larger than in M87 (even though the visible galaxy itself is only about twice as luminous as M87). Thus if the numbers of globular clusters increase in proportion to the cooling flow rate, we would expect $S(\text{N6166}) \sim 80$, a figure almost 20 times higher than what is observed. Other evidence against the cooling-flow formation picture includes: (1) M87 globulars are not distinguishable photometrically from those in other, more normal, Virgo members (see Cohen 1988; Harris 1988*b*); and (2) the metallicity of X-ray halo gas is much higher than that of typical globular clusters in these galaxies (e.g., Forman and Jones 1982).

Finally we consider the dwarf galaxies found around NGC 6166. In § III it was pointed out that the sizes of these objects were roughly consistent with the mean sizes of low luminosity dwarfs (e.g., Kormendy 1985). Extrapolating the Virgo cluster dwarf LF of Sandage, Binggeli, and Tammann (1985), assuming $\delta(m - M)_0 = 4.2$, and scaling from m_{M87} to $m_{\text{N6166}}^{\text{obs}}$, we estimate that we should have seen 36 dwarf galaxies in our "inner" region in the range $B = 25.0$–26.4. [This is probably an upper limit, because (1) dwarf galaxies are almost certainly depleted in the inner regions of galaxies due to dynamical effects, and (2) the brightness of "fuzzy" objects tends to be underestimated by DAOPHOT (by typically 0.2–0.5 mag from simulations).] In fact, $\sim$ 20–50 objects were observed. Given the uncertainties in the calculation (and especially in the extrapolation of the dwarf LF), the agreement between observed and computed numbers of dwarf galaxies must be fortuitous; nevertheless it is at least *indicative* that the population of dwarfs is not abnormal.

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