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GLOBULAR CLUSTERS IN GALAXIES BEYOND THE LOCAL GROUP. VII. THE S0 GALAXY NGC 3115

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ABSTRACT

We describe the total population and spatial distribution of globular clusters associated with the edge-on S0 galaxy NGC 3115, derived from star counts carried out upon CFHT and AAT prime focus plates. The cluster system is of specific frequency $S \approx 2$, somewhat below normal for an E/S0 galaxy but consistent with its location in a sparse environment. The spatial distribution of the globular clusters is similar to that describing the falloff of halo luminosity along the galaxy's minor axis ($\sigma \approx r^{-2}$). The cluster distribution exhibits circular symmetry within the observational errors, suggesting that the globular clusters are a more nearly pure halo component of NGC 3115 than any part of its very prominent disk or extended spheroid light. We derive a preliminary integrated luminosity function by combining star counts from several sources and deduce a distance in the range of 8–12 Mpc.

Finally, we identify a nucleated dwarf companion of NGC 3115 which itself has a globular cluster system. Furthermore, the dwarf has more clusters per unit luminosity by a factor near 3 than its parent galaxy NGC 3115; in this respect the system resembles the Fornax dwarf spheroidal as a satellite of the Milky Way galaxy.

Subject headings: clusters: globular — galaxies: individual

I. INTRODUCTION

The study of globular cluster systems in external galaxies is beginning to shed light upon the earliest star formation and chemical enrichment episodes during protogalaxy collapse, as well as elucidating the importance of subsequent mergers and interactions between galaxies (Harris 1986). An essential part of this type of study is the detection and analysis of globular cluster populations in galaxies of various types and luminosities and in a range of environments. In previous papers of this series and in associated work, the emphasis has been on the cluster systems in large elliptical galaxies (Harris and van den Bergh 1981, hereafter Paper I; Harris and Hanes 1985, hereafter Paper IV; Harris 1986, hereafter Paper V; Harris, Smith, and Myra 1983) as well as those associated with a few spiral galaxies (van den Bergh and Harris 1982, hereafter Paper II; Harris, Harris, and Harris 1984, hereafter Paper III).

In this paper we present a study of the globular clusters associated with NGC 3115, a nearby, isolated, and almost edge-on lenticular galaxy. The properties of this classic object are summarized in Table 1. It does not appear in the tabulations by de Vaucouleurs (1975) and by Huchra and Geller (1982) of nearby groups of galaxies, and it appears well isolated on Palomar Sky Survey prints. Tully (1982) mentions it as a possible outlying member of the sparse "Leo Minor Cloud." Thus NGC 3115 has a good chance of being a galaxy which may have experienced no significant environmental perturbations over its lifetime. In this respect, it is likely to have had a somewhat different history from the galaxies in the rich Virgo environment (for example) and therefore adds to the range of environments which have been investigated in the wider study of globular cluster systems.

The existence of globular clusters in the halo of NGC 3115 was first convincingly demonstrated by Strom *et al.* (1977). They derived a preliminary luminosity function as a by-product of their study of the surface brightness distribution in NGC 3115; however, the calibration was indirect, and modern photometry, preferably with CCD detectors, is still needed. Our present study is instead directed toward deriving the spatial distribution and total population of this globular cluster system through the use of wide-field photographic plates.

II. STAR COUNT DATA

We carried out star counts upon two prime focus plates obtained at the Canada-France-Hawaii Telescope (CFHT) and the Anglo-Australian Telescope (AAT); see Table 2. The AAT plate was significantly deeper than that from the CFHT, by virtue of the larger telescope aperture and the longer exposure time. However, inspection of each plate revealed an extended globular cluster system centered upon NGC 3115. In Figure 1 (Plate 16) we present a direct reproduction of the central regions of AAT plate 2090.

Our procedures for carrying out and analyzing the star counts were as described in previous papers in the series; see, for example, Paper I, or the detailed descriptions provided by Harris and Smith (1976) in a similar context. We now describe the results from the individual plates.

a) AAT Plate 2090

We each independently counted this plate, using a superposed reseau which subdivided the field into 20° sectors and 20

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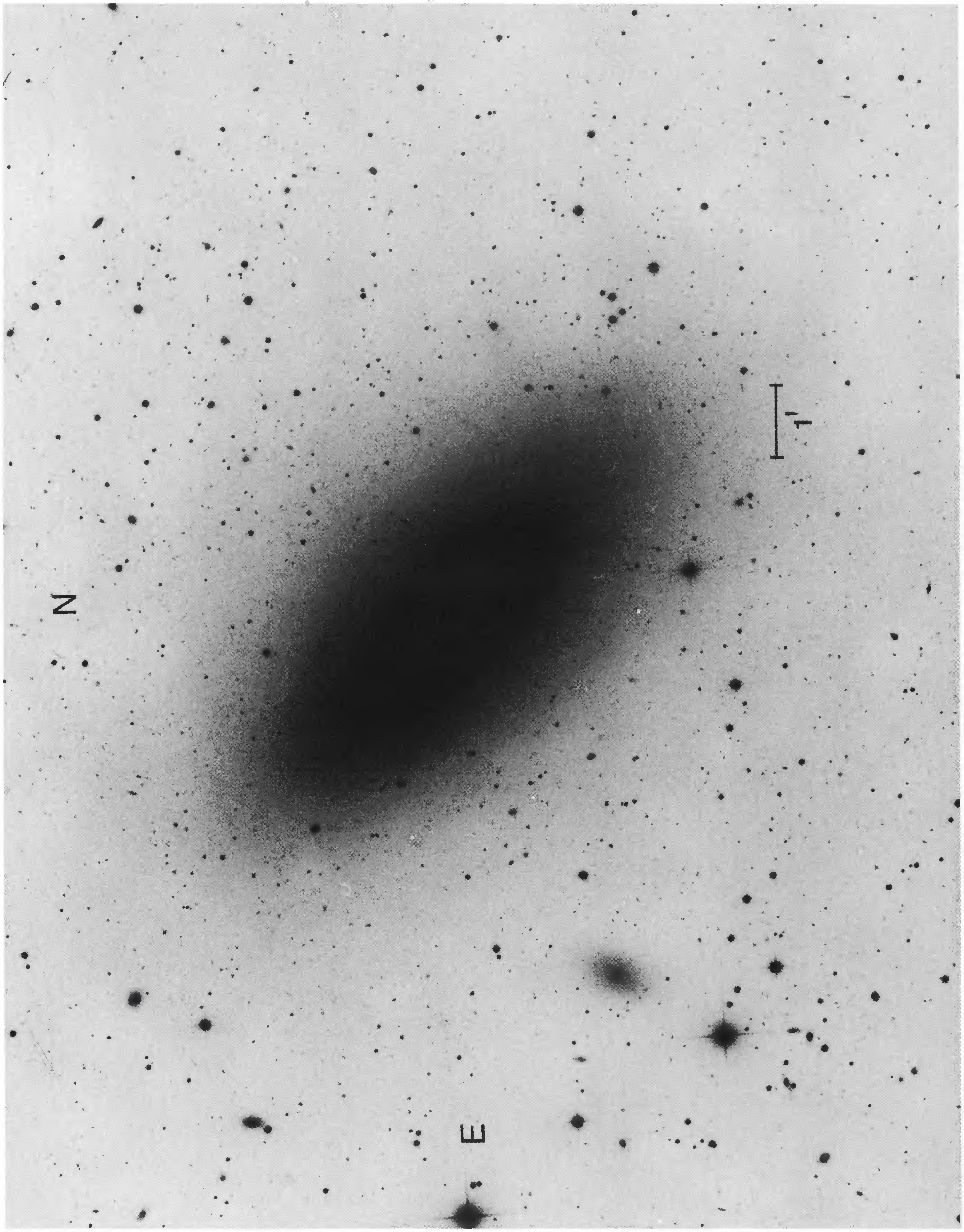

FIG. 1.—A direct reproduction of the central regions of AAT plate 2090, showing NGC 3115 and its conspicuous retinue of globular clusters. The print has been heavily exposed to emphasize the number of faint images and the highly flattened spheroidal component of the galaxy; its thin, edge-on disk and bright nucleus are in the overexposed central region. A nucleated dwarf companion (1) is visible to the east.

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TABLE 1

PROPERTIES OF NGC 3115

Property	Value	Reference
(α, δ) (1950)	$10^h02^m.74$, $-07°28'.5$	RC2
(l, b)	247°.8, 36°.8	RC2
(SGL, SGB)	112°.4, −42°.9	RC2
B_T	9.70	RC2
$(B-V)_T$	0.87	RC2
A_B	0.26	RC2
V_0	476 km s^{-1}	RC2
Type	$S0_1(7)$	RSA
Diameter $D(0)$	6'.6	RC2

REFERENCES.—RC2 = de Vaucouleurs, de Vaucouleurs, and Corwin 1976. RSA = Sandage and Tammann 1981.

annuli of width 4.35 ± 0.02 mm centered upon NGC 3115. AAT plates taken behind the triplet corrector at prime focus have a central plate scale of 15".3 mm^{-1} and suffer 1.36% pincushion distortion 30' off axis (*AAO Observer's Guide*). Since our counts extended to maximum radii of <22', the field distortion is small and was ignored.

We counted all visible images, making no effort to discriminate between those of stellar and nonstellar appearance. Counts were made for every cell in the reseau except for the following: (i) the innermost circle (centered on the galaxy); (ii) a cell in annulus 16 which contained a dwarf galaxy (see § IV); and (iii) one sector in each of the outer three annuli in a region shadowed by the guide probe. Our separate sets of count totals agreed to within 1% (indicating that our individual "limiting magnitudes" were similar), and there were no azimuthal or radial trends in the count ratios larger than the random statistical errors. For subsequent analysis we simply averaged the independent data sets cell by cell.

In Table 3A we present the radial dependence of the count surface density. Successive columns give: (1) the ring number, n; note that ring number n extends from annulus marking $(n-1)$ to n, so that ring 1 is actually the innermost circle containing the galaxy itself; (2) the effective (median) ring radius, defined by $r = \sqrt{r_i r_o}$, where r_i and r_o are the inner and outer radii of the annulus; (3) the area of the annulus bounded by radii r_i and r_o; (4) the number of objects counted in the ring, and the associated size-of-sample error; (5) the fractional completeness of the counts in the ring; (6) the surface density of counts; (7) the surface density of globular clusters, after the subtraction of a uniform surface density of 9.6 ± 0.2 field objects per square arcminute, derived as described in § III; and (8) the total globular cluster content of a given ring (i.e., col. [3] multiplied by col. [7]).

b) *CFHT Plate 3277*

Star counts were carried out on this plate by one of us (W. E. H.) with the same reseau as was used for the AAT plate and in the same manner as before. The plate scale at field center is ~13".7 mm^{-1}, and corrections for the known radial plate scale distortion were applied as described in Papers IV and V. We present the final counts in Table 3B, where the columns have the same meaning as in Table 3A except that a surface density of field objects of 5.9 ± 0.3 per square arc minute was adopted (see § III).

TABLE 2

PLATE MATERIAL EMPLOYED

Parameter	Plate AAT 2090 (1982 Mar 21/22)	Plate CFHT 3277 (1983 May 10/11)
Telescope	3.9 m AAT	3.4 m CFHT
Focus/corrector	f3.3 prime/triplet	f4.2 prime/wide field
Emulsion/filter	IIIa-J + GG385	IIIa-J + GG385
Exposure (minutes)	90	50
Seeing (arcsec)	1.0–1.5	0.7–1.0

III. ANALYSIS

a) *Background Density and Limiting Magnitude*

In Figure 2 we show the dependence of star count surface density upon radial distance in the field of NGC 3115. (Note that log σ is plotted against log r, not σ versus r as in previous papers.) For each plate, a strong central concentration of images is obvious, as is the asymptotic leveling off to a uniform surface density of field objects at radii larger than ~8'. Numerical averages over various subsets of the outermost annuli yielded the following estimates for the field object ("background") surface densities:

$$\sigma_b = 9.6 \pm 0.2(\text{AAT plate 2090}) \text{ arcmin}^{-2}$$

$$\sigma_b = 5.9 \pm 0.3(\text{CFHT plate 3277}) \text{ arcmin}^{-2}.$$

These surface densities are plotted as broken lines in the panels of Figure 2.

We have estimated the limiting magnitude of each plate by comparing the observed surface density of field objects with the predictions of a model which includes foreground stars (Bahcall and Soneira 1981) and remote background galaxies

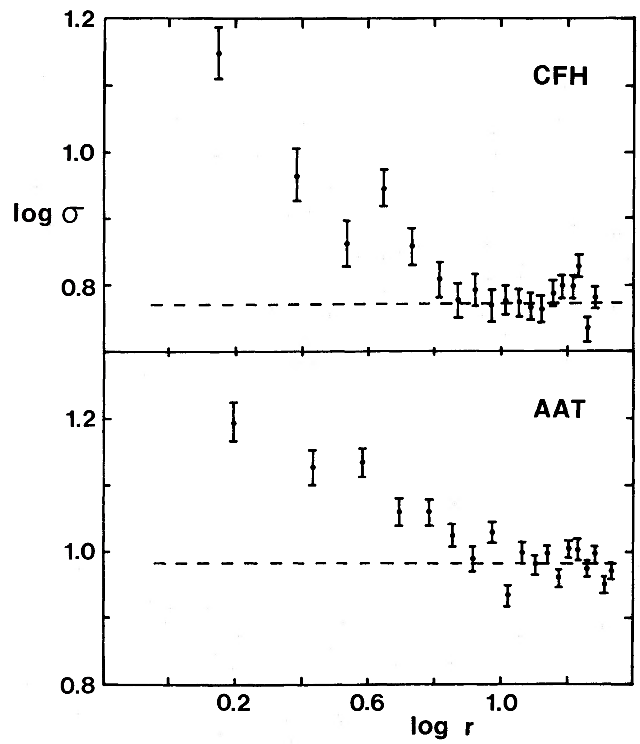

FIG. 2.—The logarithmic surface density of all counted objects within circular annuli centered upon NGC 3115, plotted vs. the logarithm of the effective radii (in arcminutes) of the annuli. The separate panels refer to the counts from CFHT plate 3277 and AAT plate 2090, as indicated. In each case a strong central concentration is obvious. The error bars are those arising from $\pm\sqrt{N}$ sampling statistics. In each panel the horizontal broken line indicates the adopted local contribution by foreground and background objects.

TABLE 3

STARCOUNTS IN NGC 3115

Ring (1)	r (arcmin) (2)	Ring Area (arcmin^2) (3)	n (4)	f (5)	σ (arcmin^{-2}) (6)	σ_{cl} (arcmin^{-2}) (7)	N_{cl} (8)
A. From AAT Plate 2090							
2.........	1.57	11.60	181.5 ± 13.5	[1.00]	15.65 ± 1.16	6.04 ± 1.18	70.1 ± 13.7
3.........	2.72	19.33	259.5 ± 16.1	1.00	13.43 ± 0.83	3.82 ± 0.86	73.9 ± 16.6
4.........	3.84	27.06	369.0 ± 19.2	1.00	13.64 ± 0.71	4.04 ± 0.74	109.2 ± 20.0
5.........	4.96	34.79	399.5 ± 20.0	1.00	11.48 ± 0.57	1.88 ± 0.61	65.5 ± 21.2
6.........	6.08	42.52	491.0 ± 22.2	1.00	11.55 ± 0.52	1.95 ± 0.56	82.8 ± 23.7
7.........	7.19	50.25	531.0 ± 23.0	1.00	10.57 ± 0.46	0.97 ± 0.50	48.6 ± 25.1
8.........	8.30	57.98	566.5 ± 23.8	1.00	9.77 ± 0.41	0.17 ± 0.46	9.9 ± 26.5
9.........	9.41	65.71	706.5 ± 26.6	1.00	10.75 ± 0.40	1.15 ± 0.45	75.7 ± 29.7
10.........	10.52	73.45	630.5 ± 25.1	1.00	8.58 ± 0.34	−1.02 ± 0.40	−74.6 ± 29.1
11.........	11.63	81.18	809.0 ± 28.4	1.00	9.97 ± 0.35	0.37 ± 0.40	29.7 ± 32.8
12.........	12.74	88.91	853.5 ± 29.2	1.00	9.60 ± 0.33	0.00 ± 0.38	0.0 ± 34.2
13.........	13.86	96.64	960.5 ± 31.0	1.00	9.94 ± 0.32	0.34 ± 0.38	32.8 ± 36.5
14.........	14.97	104.37	956.0 ± 30.9	1.00	9.16 ± 0.30	−0.44 ± 36	−45.9 ± 37.3
15.........	16.08	112.10	1139.5 ± 33.8	1.00	10.17 ± 0.30	0.57 ± 0.36	63.9 ± 40.5
16.........	17.80	119.83	1140.0 ± 33.8	0.94	10.07 ± 0.30	0.47 ± 0.36	56.8 ± 43.1
17.........	18.29	127.56	1190.0 ± 34.5	1.00	9.33 ± 0.27	−0.27 ± 0.34	−34.4 ± 42.9
18.........	19.40	135.29	1268.5 ± 35.6	0.94	9.93 ± 0.28	0.33 ± 0.34	44.4 ± 46.4
19.........	20.51	143.03	1205.0 ± 34.7	0.94	8.92 ± 0.26	−0.68 ± 0.33	−97.2 ± 46.6
20.........	21.62	150.76	1333.5 ± 36.5	0.94	9.37 ± 0.26	−0.23 ± 0.33	−35.4 ± 49.0
B. From CFHT Plate 3277							
2.........	1.41	9.31	131.0 ± 11.5	[1.00]	14.07 ± 1.23	8.17 ± 1.27	76.1 ± 11.8
3.........	2.44	15.56	143.0 ± 12.0	1.00	9.19 ± 0.77	3.29 ± 0.82	51.2 ± 12.8
4.........	3.45	21.78	159.0 ± 12.6	1.00	7.30 ± 0.58	1.40 ± 0.65	30.5 ± 14.2
5.........	4.45	27.97	247.0 ± 15.7	1.00	8.83 ± 0.56	2.93 ± 0.64	82.0 ± 17.8
6.........	5.45	34.18	247.0 ± 15.7	1.00	7.23 ± 0.46	1.33 ± 0.55	45.3 ± 18.8
7.........	6.45	40.34	260.0 ± 16.1	1.00	6.45 ± 0.40	0.55 ± 0.50	22.0 ± 20.2
8.........	7.44	46.54	279.0 ± 16.7	1.00	6.00 ± 0.36	0.09 ± 0.47	4.4 ± 21.8
9.........	8.44	52.62	327.0 ± 18.1	1.00	6.22 ± 0.34	0.31 ± 0.46	16.5 ± 24.0
10.........	9.43	58.79	346.0 ± 18.6	1.00	5.89 ± 0.32	−0.02 ± 0.44	−0.9 ± 25.6
11.........	10.42	64.89	389.0 ± 19.7	1.00	6.00 ± 0.30	0.10 ± 0.43	6.2 ± 27.7
12.........	11.41	70.90	422.0 ± 20.5	1.00	5.95 ± 0.29	0.05 ± 0.42	3.7 ± 29.6
13.........	12.40	77.03	452.0 ± 21.3	1.00	5.87 ± 0.28	−0.03 ± 0.41	−2.5 ± 31.4
14.........	13.39	82.98	482.0 ± 22.0	1.00	5.81 ± 0.27	−0.09 ± 0.40	−7.6 ± 33.2
15.........	14.37	88.90	546.0 ± 23.4	1.00	6.14 ± 0.26	0.24 ± 0.40	21.5 ± 35.5
16.........	15.36	94.88	596.0 ± 24.4	1.00	6.28 ± 0.26	0.38 ± 0.40	36.2 ± 37.5
17.........	16.34	100.84	633.0 ± 25.2	1.00	6.28 ± 0.25	0.38 ± 0.39	38.0 ± 39.4
18.........	17.32	106.55	719.0 ± 26.8	1.00	6.75 ± 0.25	0.85 ± 0.39	90.4 ± 41.7
19.........	18.30	112.33	609.0 ± 24.7	1.00	5.42 ± 0.22	−0.48 ± 0.37	−53.8 ± 41.8
20.........	19.28	118.18	714.0 ± 26.7	1.00	6.04 ± 0.23	0.14 ± 0.38	16.7 ± 44.4

(Jarvis and Tyson 1981); the method is described in Paper I. For our count limits, we deduce

$$B_J(\text{lim}) = 24.5 \pm 0.2 (\text{AAT plate 2090})$$

and

$$B_J(\text{lim}) = 23.9 \pm 0.2 (\text{CFHT plate 3277}) ,$$

where B_J represents the IIIa-J + GG385 photographic system. In our experience, these limiting magnitudes are consistent with estimates for other prime focus plates taken under similar conditions.

b) *The Distribution of Globular Clusters and a Comparison with the Halo Light of NGC 3115*

In Figure 3*a* we present the radial dependence of the background-subtracted surface density of objects associated with NGC 3115, as derived from AAT plate 2090. Figure 3*b* shows the equivalent plot for data from the CFHT plate. The innermost point in each panel, parenthesized, is likely to be an underestimate because of the obscuration of some of the sectors of ring 2 by the disc of NGC 3115. We did not merely exclude such sectors and later rescale the counts to compensate for the areal incompleteness because this assumes circular symmetry in the counts, a feature for which we test below. In Table 4 we summarize the parameters which best fit the data points when they are expressed first in a log-log representation, as in Figure 3; and then as a function which linearly relates the logarithm of the surface density to the one-fourth–power of the radius (a "de Vaucouleurs" law). (For the third set of entries in Table 4, the data were combined as described in § III*c*, below.) As has been found for most of the galaxies studied in this series, the power-law representation has an exponent near −2 (see the discussion of Paper V).

In Figures 3*a* and 3*b* the superposed curve represents the surface intensity in V light along the *minor axis* of the galaxy (Strom *et al.* 1977), scaled by eye to yield a reasonable fit to the globular cluster data points. The falloff of surface intensity along the minor axis is presumably more representative of the halo of NGC 3115 than would be the major axis profile, which is strongly affected by the disk. If this assumption for the minor

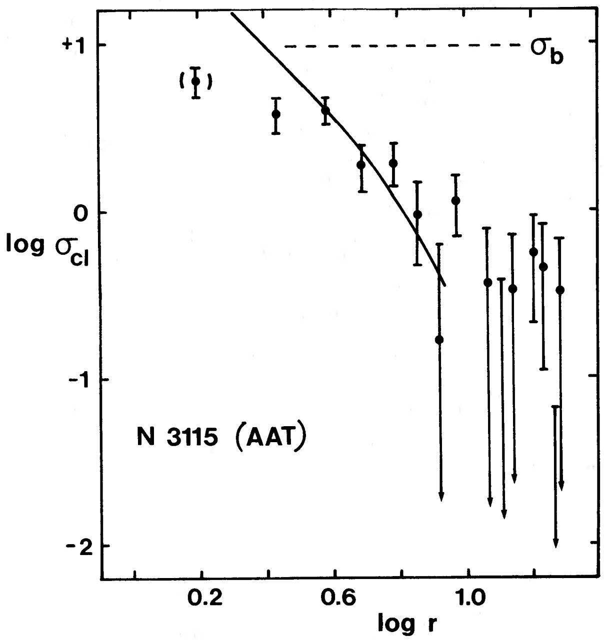

FIG. 3*a*

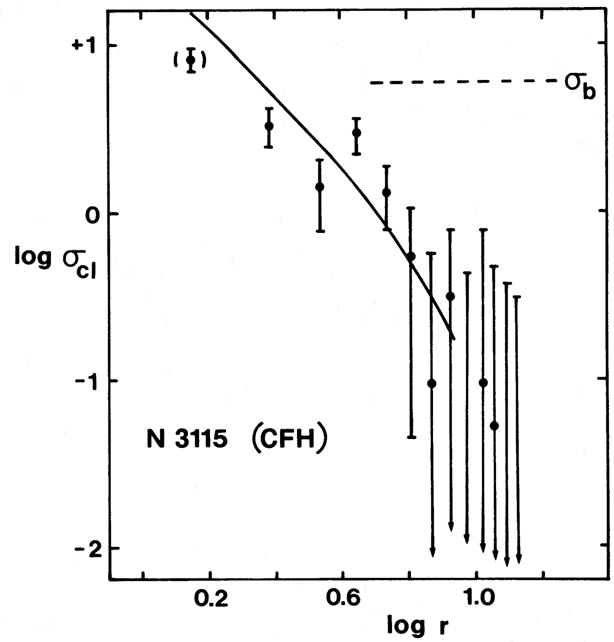

FIG. 3*b*

FIG. 3.—(*a*) The logarithmic plot of residual (= globular cluster) surface density, after the subtraction of field objects, as a function of radius for the data from AAT plate 2090. The horizontal broken line shows the adopted field surface density. The solid curve represents the surface brightness profile (in *V*) derived by Strom *et al.* (1977) along the minor axis of NGC 3115. An arbitrary zero-point shift has been made. (*b*) As in (*a*), except that in this case the data are from CFHT plate 3277.

axis is correct, the figures then demonstrate that the spatial distribution of globular clusters is matched reasonably well by the distribution of halo light, as has been shown to be the case for the large spiral galaxies NGC 4565 and NGC 4594 (Papers II and III). Among the large elliptical galaxies, there are striking exceptions to this statement which may be indicative of different dynamical histories or formative processes (Forte, Martinez, and Muzzio 1982; Muzzio, Martinez, and Rabolli 1984; but see Paper V).

In Figure 4 we present the azimuthal dependence of the surface density of counted objects around NGC 3115, summed over 40° sectors and over rings 2–10 inclusive (to sharpen the contrast of the globular cluster system to the background). Because NGC 3115 has such a strong disk and highly flattened spheroid component (Strom *et al.* 1977), we expected to find at least some trace of this in the cluster distribution. Surprisingly, *no strong dependence of surface density upon position angle* is evident, although there may be a slight tendency for a *lower* surface density to be found in the plane of the disk, i.e., along the major axis. This is contrary to expectation if the globular cluster distribution were to mimic the distribution of spheroidal luminosity of its parent galaxy and is also inconsistent with a purely spherical (halo-like) distribution. However, we have noted that the innermost rings may be slightly incomplete, an effect which would be stronger in the plane of the disk and which would lead naturally to the dependence seen in Figure 4. Given the very marginal size of the asymmetry, we prefer to conclude that the globular cluster distribution in NGC 3115 is consistent with a purely spherical one.

c) Specific Frequency and Distance

The specific frequency *S* of a globular cluster population associated with a galaxy was introduced in Paper I. By definition, *S* is the number of clusters per unit ($M_v = -15$) luminosity of the parent galaxy. This quantity takes into account the largely direct scaling of cluster population with galaxy luminosity (Hanes 1977) and allows the identification of galaxies with anomalously rich or poor globular cluster populations.

We first estimate the total observed population of clusters on our two plates. On AAT plate 2090, we counted 4944 images in rings 2–11 inclusive. Subtraction of the background contribution (at $\sigma_b = 9.6 \pm 0.2$ per square are minute) leaves an excess of 491 ± 116 globular clusters. If the central (obscured) ring has an extrapolated cluster surface density of ~ 7 per square arc minute, the total changes to $N_{cl} \approx 520 \pm 120$ globular clusters brighter than $B_J = 24.5 \pm 0.2$. Similar calculations for CFHT plate 3277 yield 360 ± 90 clusters down to $B_J = 23.9 \pm 0.2$, a factor of 0.69 fewer than detected on the

TABLE 4

STRUCTURE OF GLOBULAR CLUSTER DISTRIBUTION

Data Set	Value
AAT plate, rings 3–14	$\log \sigma_{cl} = (-1.88 \pm 0.29) \log r + (1.51 \pm 0.19)$
	$\log \sigma_{cl} = (-2.19 \pm 0.32)\, r^{1/4} + (3.50 \pm 0.50)$
CFHT plate, rings 3–14	$\log \sigma_{cl} = (-1.82 \pm 0.38) \log r + (1.26 \pm 0.24)$
	$\log \sigma_{cl} = (-2.17 \pm 0.44)\, r^{1/4} + (3.26 \pm 0.40)$
Combined data, $r < 13'$	$\log \sigma_{cl} = (-1.84 \pm 0.23) \log r + (1.46 \pm 0.15)$
	$\log \sigma_{cl} = (-2.16 \pm 0.26)\, r^{1/4} + (3.44 \pm 0.30)$

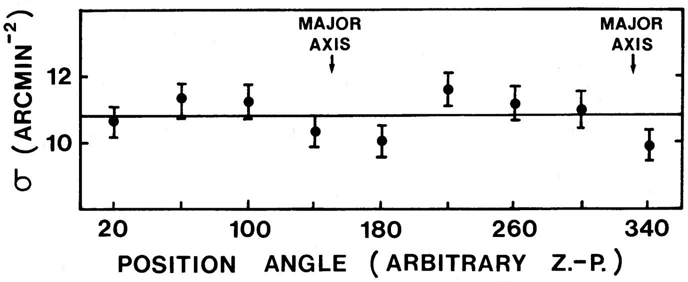

FIG. 4.—The azimuthal dependence of the surface density of counted objects in the field of NGC 3115, summed over 40° sectors and over annuli 2–10 inclusive. The error bars are those arising from $\pm\sqrt{N}$ statistics, and the solid horizontal line indicates the surface density averaged over all nine sectors. The position angle is of arbitrary zero-point, but the orientation of the major axis of the galaxy is indicated.

AAT plate. In Figure 5 we present a composite radial distribution of the two data sets, where we have scaled up the CFHT counts by a factor $(0.69)^{-1} = 1.44$. The good match between the two data sets shows that the radial gradient in globular cluster surface density is the same to the different magnitude limits, a conclusion which was already implied by the reasonable fits in the separate panels of Figure 3.

The determination of S for NGC 3115 next requires an assumed distance so that the apparent magnitude of the galaxy and the cluster sample size may be converted to absolute luminosity and total population. However, the distance to NGC 3115 is not well known. Its corrected recession velocity of ~ 450 km s^{-1} (de Vaucouleurs, de Vaucouleurs, and Corwin 1976; Sandage and Tammann 1981) suggests a distance of 5–10 Mpc, depending upon the choice of local Hubble parameter, but the estimate is sensitive to the peculiar motions of our own Galaxy and NGC 3115 itself. Furthermore, since NGC 3115 is not a member of a clearly defined small group, no mean group radial velocity can reliably be referred to.

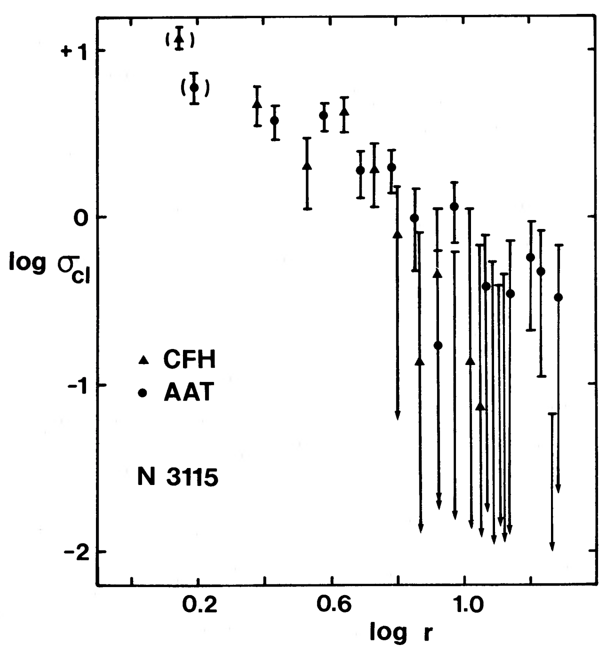

FIG. 5.—A composite of the residual surface densities of globular clusters deduced from each plate, plotted as a function of radius. The CFHT counts have been scaled up by a factor of 1.44 as described in the text.

Unfortunately, since no Population I indicators are present, no direct distance measurement methods independent of H_0 are available for this galaxy, except for the luminosities of the globular clusters themselves (see the discussion below). Strom *et al.* (1977) deduced a distance of about 10 Mpc through a direct intercomparison of the cluster luminosity functions in M31 and NGC 3115. However, the M31 function they used (van den Bergh 1969) is incomplete at faint levels (Racine and Shara 1979; Crampton *et al.* 1985), and the same appears to be true for their NGC 3115 function, as our new data suggest. Although these two effects would at least partly cancel out, it is not immediately clear how the distance estimate would be affected.

Although a full, photometrically calibrated luminosity function (LF) for the cluster system is not yet available, a somewhat cruder "four-point" LF can be assembled and used to place limits on the distance. The two population totals above can be augmented by adding in results from two other studies. S. van den Bergh (private communication) has carried out star counts upon a short-exposure plate taken at the Dupont 2.5 m telescope; he detects no significant numbers of globular clusters down to $B_J(\lim) = 21.0 \pm 0.5$ (as estimated from the uniform surface density, $\sigma_b = 1.18 \pm 0.05$ per square arc minute, of images across the plate). We adopt $N_{cl} \approx 0 \pm 30$ to this level. Finally, from Figure 4 of Strom *et al.* (1977) we adopt a lower limit of 187 clusters brighter than $B_J(\lim) \approx 23.25$ since their function refers to objects found within a limited area of 20 square arc minutes around the galaxy center.

These four estimates are plotted as a function of limiting magnitude in Figure 6, where it can be seen that the observed total increases smoothly with limiting magnitude. To estimate the true total population N_t of clusters over all magnitudes, we go through the following procedure: first, assume that there is a universal globular cluster LF which is well represented by a normal curve of mean absolute magnitude $M_J = -6.8$ and intrinsic dispersion $\sigma = 1.20$ mag (Harris and Racine 1979; Hanes 1979). Then (see Paper I), the observed number N_{cl} at a given $B_J(\lim)$ can be converted into a total population by assuming a distance and correcting the count for the fraction of the normal curve lying fainter than the plate limit. The important point is that if we *have* assumed the correct distance then every one of the $N_{cl}(B)$ totals should give the *same* total population N_t. (See Paper III for a similar argument used to estimate the distance to NGC 4594.) This means in practice that we can simultaneously place limits on both S and the galaxy distance.

We have carried out these estimates of N_t for various assumed distances from 5 to 15 Mpc; the most plausible range of results is summarized in the curves shown in Figure 6. The two lines indicate the expected number of observed clusters for a population of $N_t = 500$ clusters at a distance of 8 Mpc, or for $N_t = 700$ clusters at a distance of 12 Mpc. Both curves match the four data points within their observation errors and suggest that NGC 3115 is ~ 10 Mpc distant, in agreement with the Strom *et al.* value. From the globular cluster data alone, and from the assumption about the universality of the globular cluster LF, it appears unlikely that NGC 3115 is any nearer than ~ 7 Mpc or more distant than ~ 13 Mpc.

The total visual magnitude of NGC 3115, corrected for foreground and internal obscuration, is $V_T = 8.83$ mag (de Vaucouleurs, de Vaucouleurs, and Corwin 1976). In Table 5 we summarize the calculations of specific frequency S which are implied by each of our two choices of distance (8 or 12 Mpc).

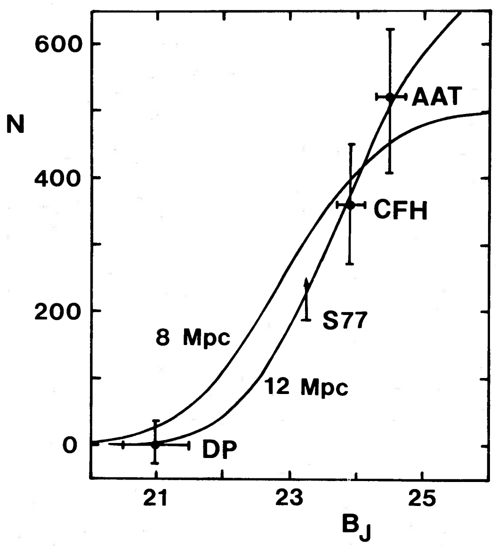

FIG. 6.—A provisional integrated luminosity function for the globular clusters associated with NGC 3115. Here N is the total number of observed globular clusters brighter than limiting magnitude B_J. The four data points come from AAT plate 2090, from CFHT plate 3277, from the study by Strom *et al.* (1977), which yields a lower limit denoted S77, and from a Dupont reflector plate (labeled DP) studied by van den Bergh (see § III of the text). The superposed curves show the expected behavior of a normal distribution of globular clusters with mean absolute magnitude $M_J = -6.8$ and intrinsic dispersion 1.2 mag at a distance of 8 Mpc (with a total population of 500 clusters) or at a distance of 12 Mpc (with 700 clusters in total).

The quoted uncertainties in S are formal internal ones and reflect the propagation of the size-of-sample uncertainties in the two sets of star counts. It will be seen from the table that, in contrast to the situation for the Virgo galaxies, S is rather sensitive to the assumed distance. This is because our star counts reached deep enough to go well below the turnover of the cluster LF (which lies at $M_J = -6.8$, or $B_J = 23.3$ if $d \approx 10$ Mpc) and thus include the majority of the cluster population. Changing the assumed distance changes the galaxy luminosity but has little effect on N_t, and the ratio S changes noticeably. By contrast, the star counts for the more distant galaxies (such as those in Virgo) stop close to the turnover of the LF, so that both M_v (galaxy) and N_t change at about the same rate with assumed distance.

Our conclusion is that the specific frequency for NGC 3115 is likely to lie in the range $S = 2 \pm 1$. No more precise statement seems possible at present, given the remaining uncertainty in the distance. Nevertheless, it is clear that this S0 galaxy has a far smaller cluster population relative to its luminosity than do the Virgo ellipticals (where $S_{av} \approx 6$). Values of S in the range of about 2–4, do, however, seem rather typical among big galaxies located in sparse environments (see Papers I and V). Even the giant Sa system NGC 4594 (Paper III) has

TABLE 5

ESTIMATES OF SPECIFIC FREQUENCY FOR NGC 3115

PARAMETER	ASSUMED DISTANCE 8 Mpc	12 Mpc
True distance modulus	29.51	30.40
Absolute magnitude	−20.68	−21.57
Cluster content	500 ± 120	700 ± 170
S	2.7 ± 0.6	1.7 ± 0.4

TABLE 6

PROPERTIES OF DWARF COMPANIONS

Parameter	Dwarf 1 (Kara 68-065)[a]	Dwarf 2 (MCG 01-26-021)[b]
(α, δ) (1950)	$10^h03^m06^s$, $-07°30'.6$	$10^h03^m13^3$, $-07°44'.4$
B mag	16.0 ± 0.2	14.2 ± 0.2
Visible dimensions (major axis)	~20″	~45″
Classification	dE4, N	dE1, N

[a] Karachentseva 1973.
[b] Vorontsov-Velyaminov *et al.* 1962–1974.

$S \approx 3$. In this respect, NGC 3115 therefore seems to follow the normal trend of specific frequency with environment displayed by late-type galaxies.

IV. THE DWARF COMPANIONS

Two nucleated dwarf companions of NGC 3115 fell within our star count region. Their positions, dimensions, and magnitudes (derived as described below) are summarized in Table 6. Dwarf 1, the smaller and fainter, is ~7′ east of NGC 3115, while dwarf 2 is ~17′ to the southeast. Both are structurally similar to the dE, N dwarfs cataloged by Sandage and Binggeli (1984); they possess sharp nuclei surrounded by faint diffuse halos. The nucleus of dwarf 1 is completely starlike on our plates of best seeing (0″.7) but the nucleus of dwarf 2 is only semistellar, with a diamter of ~2″ from visual inspection (corresponding to ~100 pc for a distance of 10 Mpc).

In Figure 7 (Plate 17) we reproduce a direct print of dwarf 2, the outer and brighter companion. Inspection of the plate during the course of our star counts showed that this dwarf, surprisingly, possesses a quite noticeable cluster population. Counts made locally in the smaller region around the dwarf (with a more finely graduated reseau) revealed an excess of 25 ± 10 objects above the local background. On average, these objects are similar in brightness to the clusters around NGC 3115 itself. The fainter, inner dwarf (1) showed no such excess. We also note that Sandage and Binggeli (1984; see their Panel 4 illustration and their comments on p. 927) suspected one of their Virgo dE, N galaxies (9°.25) of having an incipiently resolved cluster population.

We have estimated the luminosities of the NGC 3115 dwarfs by comparing them with Sandage-Binggeli Virgo dwarfs of similar appearance. For each of the two, we identified nine or 10 Virgo dwarfs on the Palomar Observatory Sky Survey (blue) prints which by eye inspection had similar sizes and luminosities, and then averaged their B magnitudes to obtain the results quoted in Table 6. In each case, the dwarfs used for comparison were of similar B magnitude, to within ±0.3 mag about the mean.

If dwarf 2 is assumed to have a color $B - V = 0.8 \pm 0.2$, a typical value for a low-luminosity elliptical, then its total visual magnitude is $V_T \approx 13.4 \pm 0.3$. It is of obvious interest to find the specific frequency of its cluster population. Calculations similar to those in § III reveal that S for dwarf 2 is 8.5 ± 4.0 (if $d = 8$ Mpc) or 4.6 ± 2.2 (if $d = 12$ Mpc). More to the point, we can estimate the ratio of specific frequencies of the dwarf and NGC 3115 itself. Almost independent of distance, this ratio has a value of ~3. That is, *the dwarf galaxy has a much higher number of clusters per unit luminosity than does its far bigger parent*—instead of being similar to the ellipticals in sparse groups, it is closer to the big Virgo ellipticals in specific frequency. In this respect, the NGC 3115 system is comparable to

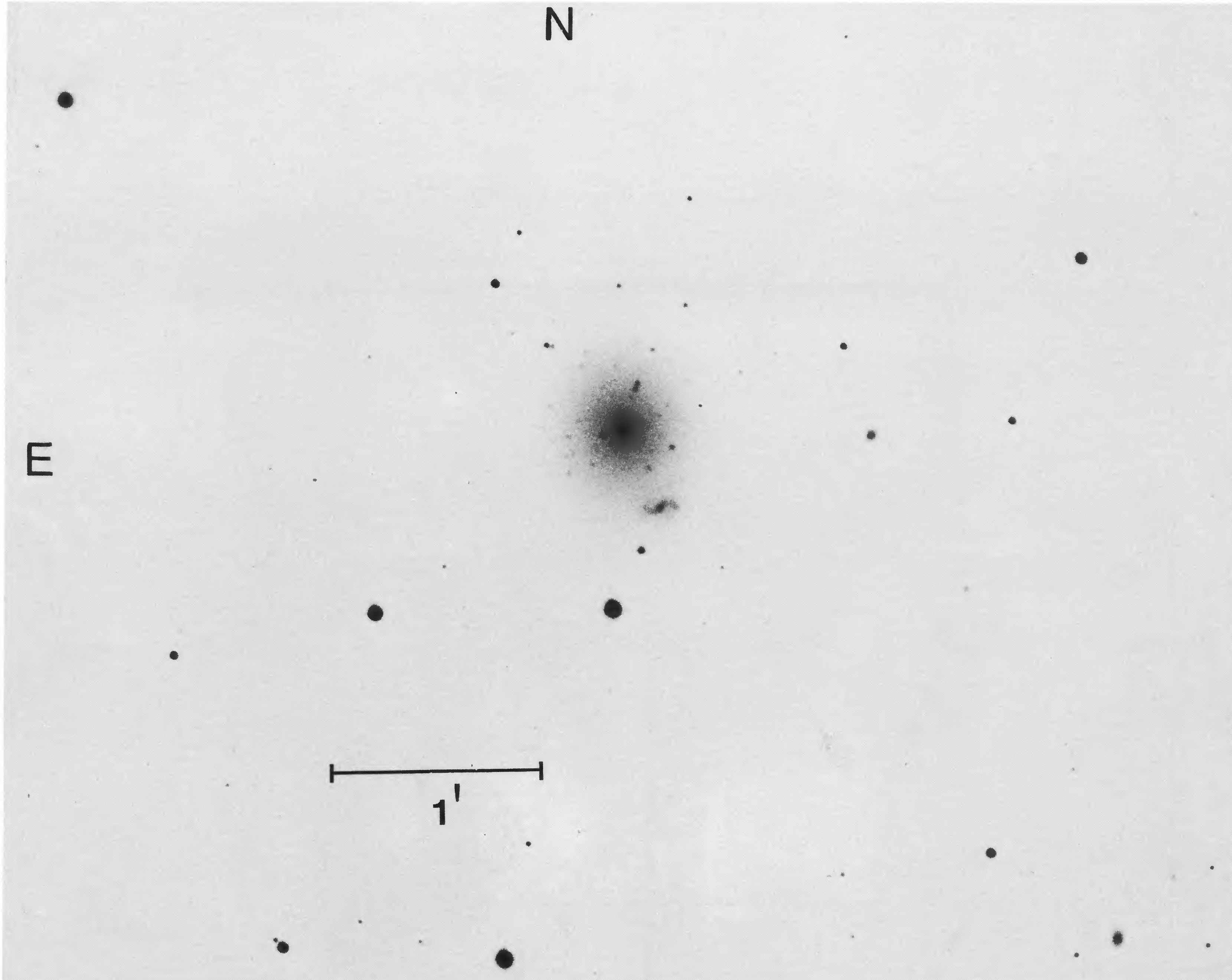

FIG. 7.—A direct reproduction of dwarf galaxy 2 as it appears on AAT plate 2090. A centrally concentrated excess of objects above the local background is apparent.

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TABLE 7

STARCOUNTS IN THE FIELD OF DWARF 2

Ring (1)	$\bar{r}$ (arcmin) (2)	Ring Area (arcmin^2) (3)	n (4)	f (5)	σ (arcmin^{-2}) (6)	σ_{cl} (arcmin^{-2}) (7)	N_{cl} (8)
2.........	0.15	0.10	5.0 ± 2.2	1.00	50 ± 22	37 ± 23	3.7 ± 2.3
3.........	0.25	0.17	9.0 ± 3.0	1.00	54 ± 18	41 ± 18	6.9 ± 3.0
4.........	0.36	0.23	9.0 ± 3.0	1.00	39 ± 13	27 ± 13	6.1 ± 3.1
5.........	0.46	0.30	7.0 ± 2.7	1.00	23 ± 9	11 ± 9	3.2 ± 2.8
6.........	0.56	0.37	8.0 ± 2.8	1.00	22 ± 8	9 ± 8	3.3 ± 3.0
7.........	0.67	0.43	9.0 ± 3.0	1.00	21 ± 7	8 ± 7	3.6 ± 3.2
8.........	0.77	0.50	10.0 ± 3.2	1.00	20 ± 6	7 ± 7	3.7 ± 3.4
8.........	0.87	0.57	6.0 ± 2.5	1.00	11 ± 4	-2 ± 5	-1.2 ± 2.9
10.........	0.98	0.63	9.0 ± 3.0	1.00	14 ± 5	2 ± 5	1.1 ± 3.4
11.........	1.08	0.70	9.0 ± 3.0	1.00	13 ± 4	0 ± 5	0.2 ± 3.5

NOTE.—$\sigma_b = 12.6 \pm 2.6$ determined from outermost three annuli.

(but not as extreme as) the Milky Way and its companion the Fornax dwarf: Fornax possesses five or six globular clusters (Hodge 1974) and has the very high specific frequency of $S \approx 20$, compared with $S \approx 2$ for the Milky Way halo (Harris 1981).

Finally, in Table 7 and Figure 8 we present the results of some star counts carried out upon an enlarged positive print of dwarf 2, in a rough attempt to estimate the radial distribution of its tiny cluster system. (The columns of Table 7 have the same meaning as did those of Table 3. Although the field object surface density is less precisely known here, the uncertainty in the net cluster count is dominated by the small number statistics [col. (4)] in the new counts, so we did not attempt to refine the estimate for the field.) As shown in the figure, the distribution is again adequately represented by a line of slope -2 in a log σ versus log r plot, although the large relative errors set only modest constraints on the slope. One important difference here as compared with NGC 3115 itself is, of course, that the clusters can be seen all the way in to the center of the dwarf. The low value of σ for the innermost ring is therefore significant and represents a real flattening off of the cluster distribution toward the nucleus. This phenomenon has been strongly suspected to occur in the much larger galaxies as well (see Paper V) but not yet clearly proven.

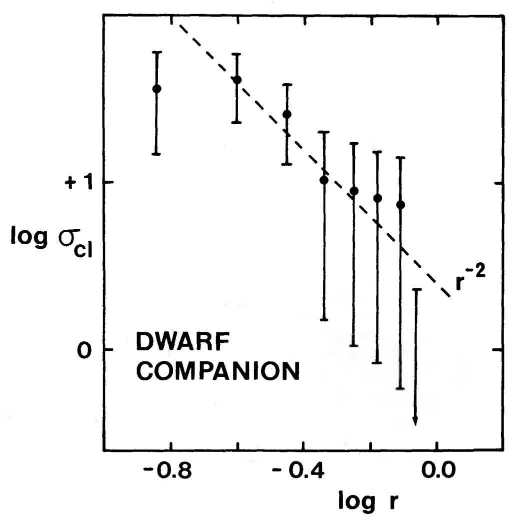

FIG. 8.—The surface density of excess objects in the field of dwarf galaxy 2, plotted vs. the logarithm of the annular radius. The error bars are those arising from sampling statistics and the subtraction of field objects. The broken line represents a power law of slope -2; it has been scaled by eye roughly to fit the data points.

To this point in the history of globular cluster system studies, the "large" cluster population in the Fornax dwarf has generally been regarded as a curious and probably unimportant anomaly, most likely the chance result of small-number statistics or of an odd dynamical evolution. The discovery of a comparable case among the NGC 3115 dwarfs now changes the picture considerably. The underlying hint is that "large" cluster systems might be much more common than was previously realized, and not just the province of the giant ellipticals at the centers of rich groups. The tiny dwarf ellipticals may develop into a much more important class in the understanding of globular cluster systems.

There is, of course, a chance that not all of the cluster in the dwarf companion are "true" globular clusters in the sense that they are primordial halo objects. A possible explanation for this intriguing situation is that the nucleated dwarf may be the gas-stripped remnant of a former small disk galaxy (see, for example, Kormendy 1985). If so, and if the encounter responsible for the stripping took place some billions of years ago, then many or most of its clusters that we now see may actually be intermediate-age disk clusters rather than true halo globulars, thus creating a spuriously high specific frequency. However, it should be noted that none of the clusters in the Fornax dwarf show any evidence for this effect; their color-magnitude diagrams (Verner *et al.* 1981; Buonanno *et al.* 1985) are the same as those of the old classical clusters. Future CCD multicolor photometry of the clusters in the NGC 3115 dwarf might help to settle the question of their nature, since intermediate-age clusters can be distinguished to some extent by their integrated colors. If all the clusters in these small ellipticals are indeed old globulars, it will become extremely important to investigate how such systems can have been many times more efficient at forming clusters then were the big ellipticals which are thought of as the more normal homes for globular clusters.

V. DISCUSSION AND CONCLUSIONS

We have identified a globular cluster population associated with the nearby and apparently isolated S0 galaxy NGC 3115. The distribution of clusters is similar to that of the light along the minor axis. In particular, there is no evidence that the globular cluster distribution is elongated in the sense of the disk component of NGC 3115. This supports the identification of the globular clusters as a pure halo population (and, by inference, as older than the bulk of the galaxy). The results of previous papers in the series indicate that the globular cluster populations within large galaxies are likely to have formed systematically earlier than the bulk of the visible regions of their parent galaxies (even earlier than the halo stars). The galaxy NGC 3115, apparently a large and well-isolated system, is in accordance with this picture. Unfortunately, because of its isolation, it sheds no light upon the importance of mergers and interactions on the global properties of cluster systems. All that can be said is that its specific frequency and spatial distribution are generally similar to those found in ellipticals within other sparse groupings.

On the basis of a preliminary integrated luminosity function for its globular clusters, we deduce a distance in the range 8–12 Mpc for NGC 3115. This estimate assumes that the intrinsic globular cluster luminosity function is the same as in the Local Group galaxies, but NGC 3115 is close enough that deep photometry will allow a direct test of this assumption (for the *shape* of the function, but not of course the zero-point). Multicolor photometry would allow some discrimination by color of field objects and would yield a more precise differential luminosity function with a correspondingly better estimate of the distance. Indeed, this is the most promising avenue for determining that distance: NGC 3115 lacks the Population I indicators which would make the determination of its distance straightforward, and it is too close for the application of Hubble flow arguments.

Although the estimate is sensitive to the assumed distance, the total cluster population of NGC 3115 suggests that this galaxy has a specific frequency in the range $S = 2 \pm 1$. This is low for an elliptical galaxy but seems to confirm the suggestion first made by Harris and van den Bergh (Paper I) that galaxies in sparse environments are deficient in globular clusters relative to those in richer surroundings. The mounting evidence seems to indicate that the efficiency of globular cluster formation near or before the time of protogalaxy collapse is strongly sensitive to environmental influences.

Finally, we have discovered that one of the companion dE galaxies around NGC 3115 has relatively more globular clusters (by a factor of near 3) than its parent galaxy NGC 3115; the system is reminiscent of the Fornax dwarf spheroidal in attendance upon the Milky Way.

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