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THE NGC 5128 GLOBULAR CLUSTER SYSTEM: STAR COUNTS IN U, V, AND R[1]

GRETCHEN L. H. HARRIS
University of Waterloo and Dominion Astrophysical Observatory
JAMES E. HESSER[2]
Dominion Astrophysical Observatory
HUGH C. HARRIS
McMaster University
AND
PATRICK J. CURRY[3]
Dominion Astrophysical Observatory
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ABSTRACT

Star counts in U, V, and R within $\sim$23 arcmin of the nearby peculiar elliptical galaxy, NGC 5128, show 800–900 counted objects in excess of background in the region studied. The cluster system inferred from these data seems to follow an $r^{1/4}$ law distribution for $r \gtrsim 4'$. Inside this radius it is possible that the clusters are deficient relative to the halo light. Using data from other studies, a cluster luminosity function over a range of 5 mag has been constructed. It agrees with the Local Group globular cluster luminosity function over the full range if the distance to NGC 5128 is $\lesssim$4 Mpc. Our analysis of the counts suggests a total cluster population of $1200 \lesssim N_t \lesssim 1900$, a specific frequency of $3.0 \lesssim S \lesssim 3.2$ and a distance of $\sim$3–4 Mpc. Larger distances are permitted only if the luminosity function is nonstandard; in such a case then $S \ll 3$ or $N \gg 2000$.

Subject headings: clusters: globular — galaxies: individual — luminosity function

I. INTRODUCTION

Although the unusual elliptical galaxy NGC 5128 is a relatively well-studied object (for a recent review see Ebneter and Balick 1983), investigations as recent as 1979 indicated that it possessed no significant globular cluster system (cf. Sersic 1960; Evans and Harding 1961; de Vaucouleurs 1979; van den Bergh 1979). With Graham and Phillips's (1980) discovery of a single bright globular cluster near NGC 5128, the door was opened to renewed effort at detecting clusters and defining the nature of the system as a whole. Subsequently van den Bergh, Hesser, and Harris (1981, hereafter BHH) and Hesser *et al.* (1984, hereafter HHBH) identified a number of cluster candidates by visual inspection and photographic microdensitometry of plates taken with the CTIO 4 m telescope; a total of 26 globular clusters have now been confirmed by spectroscopic data. Also, based on star counts from film copies of two UK Schmidt plates containing NGC 5128, they inferred a total cluster population of $\sim$600 above plate limit. Difficulties hampering discovery of the system were probably related to a combination of its low galactic latitude (resulting in field contamination by foreground stars) and its proximity (which increases the angular size, thereby making it less obvious against the field).

In this paper we report new star counts in U, V, and R light on several good CTIO 4 m prime focus plates of NGC 5128 in order to (a) compare with the previous counts done on Schmidt plates, and (b) investigate the effects of different filter-emulsion combinations on the result. It was hoped that the larger scale of the prime focus plates might increase our ability to discriminate against background galaxies, close double stars, etc. A companion study to this paper (Harris *et al.* 1984; hereafter HHHM) includes further star counts using automated techniques.

II. THE COUNTS

We chose to count images on three separate plates covering the widest possible color range available to us. (The relevant information on these plates is given in Table 1.) Plates P2110 and P5719 were kindly lent to us by R. J. Dufour and R. M. Humphreys, respectively. All plates were counted using

[1] Contributions of the University of Waterloo Observatory.
[2] Visiting Astronomer, Cerro Tololo Inter-American Observatory, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
[3] Summer student, 1982.

TABLE 1
4 m PRIME FOCUS PLATES USED FOR STAR COUNTS

Plate	Date	Observer[a]	Exposure (min.)	Emulsion	Filter	m_{lim} (magnitudes)
P2110	1976 June 21	RJD	45	103aO	UG2	21.5–22.0
P5236[b]	1981 Apr 1	JEH	15	IIaD	GG495	22.2
P5719[b]	1982 Mar 19	DM	40	IIIaF	RG610	22.0

[a] RJD: Dufour; JEH: Hesser; DM: McElroy.
[b] Plate taken with Pickering-Racine prism.

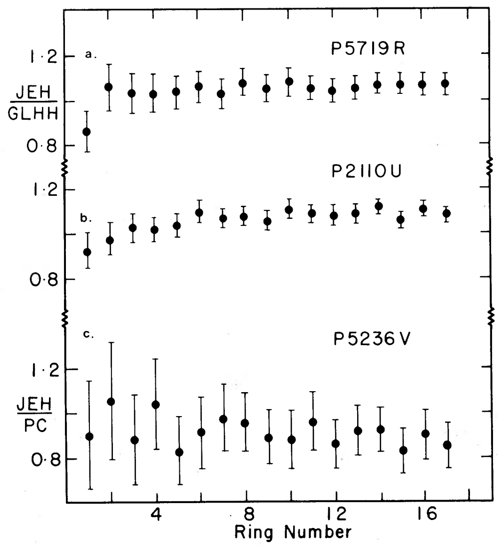

FIG. 1.—Comparison of counts by JEH and GLHH on (*a*) the *R* and (*b*) the *U* plate along with (*c*) the comparison of counts by J.E.H. and P.C. for two sectors on the *V* plate. Error bars indicate rms errors; these errors are larger for the *V* plate due to the smaller data sample.

reseaux ruled in concentric rings and divided into 18 20° sectors. The *V* plate (P5236) was counted in its entirety by only one of us (PC) with two sectors counted separately (by JEH) to provide a comparison with the results on the other two plates. The *U* (P2110) and *R* (P5719) plates were counted completely by two of us (JEH and GLHH). In all cases the counts were made alternately in and out on consecutive sectors which were themselves chosen to be counted in a random order. All images except obviously nonstellar ones (i.e., galaxies, probable plate flaws, etc.) were counted. On each plate a central circle ~1.′5 in radius was excluded, as were those sectors in rings 1, 2, and 3 containing obvious dust. The total counts for these rings were obtained by calculating a mean count for apparently dust-free sectors and multiplying by 18.

The two sets of counts on plates P5719 and P2110 are compared in Figure 1 in which we plot the ratio of JEH to GLHH counts vs. ring number for each plate. It is clear that, except for the inner ring and minor radial effects, the counts compare well with each other; the mean count ratios (i.e., JEH/GLHH) are 1.04 ± 0.01 (*U*) and 1.08 ± 0.01 (*R*). The results for the inner ring are entirely acceptable considering the effects of the galaxy itself in this region. We, therefore, used a simple average [n = (JEH + GLHH)/2] for the subsequent analysis. A similar plot for plate P5236 is shown in Figure 1. Here, however, the data are for only the two sectors counted by both JEH and PC. In this case as well, the agreement between counters is satisfactory with a mean ratio (i.e., JEH/PC) of 0.92 ± 0.02. The P5236 counts were thus assumed to be comparable to those on P5719 and P2110. The results for all three plates are given in Table 2 in which we list ring number, mean radius, ring area, total counts for each ring, and surface density. (The errors given for n and σ are rms errors.) Since the 4 m telescope optics are known to produce a radially dependent change in plate scale, both the mean radius and ring area were corrected following Chiu (1976). Counts were not carried out beyond $r \sim 23'$ since image distortion effects were already becoming noticeable.

In Figure 2 we show the radial variation of surface density, σ, for all three plates and dashed lines indicating the approximate background values adopted. Note that assigning a background value may be complicated by the presence of globular clusters in our assumed background region (discussed further in § III). While Figure 2 suggests that global radial fluctuations occur for σ in the outer rings, statistically they do not appear to be significant, nor do they seem to be correlated. In order to

TABLE 2

STAR COUNTING DATA

	Plate P5719*R*				Plate P5236*V*				Plate P2110*U*			
Ring No.	r[a]	Area[b]	n	σ[c]	r[a]	Area[b]	n	σ[c]	r[a]	Area[b]	n	σ[c]
1[d]...........	1.98	17.6	286	16.28 ± 0.96	1.91	16.2	209	12.91 ± 0.89	1.98	17.6	172	9.76 ± 0.74
2[d]...........	3.37	28.3	409	14.43 ± 0.71	3.23	26.6	348	13.09 ± 0.70	3.37	28.3	213	7.51 ± 0.51
3[d]...........	4.73	40.2	632	15.71 ± 0.62	4.58	40.4	451	11.17 ± 0.52	4.73	40.2	273	6.79 ± 0.41
4	6.08	48.2	728	15.10 ± 0.56	5.98	52.2	508	9.73 ± 0.43	6.08	48.2	336	6.97 ± 0.38
5	7.43	62.6	930	14.86 ± 0.49	7.36	63.4	658	10.36 ± 0.40	7.43	62.6	434	6.94 ± 0.33
6	8.77	73.6	994	13.50 ± 0.43	8.74	76.1	685	9.01 ± 0.34	8.77	73.6	408	5.54 ± 0.27
7	10.10	82.7	1174	14.20 ± 0.42	10.11	85.4	749	8.77 ± 0.32	10.10	82.7	528	6.39 ± 0.28
8	11.42	96.8	1336	13.80 ± 0.38	11.47	98.9	945	9.56 ± 0.31	11.42	96.8	553	5.71 ± 0.24
9	12.76	105.9	1288	12.19 ± 0.34	12.84	108.8	886	8.14 ± 0.27	12.76	105.9	583	5.50 ± 0.23
10	14.08	116.1	1534	13.22 ± 0.34	14.13	117.9	961	8.91 ± 0.29	14.08	116.1	668	5.75 ± 0.22
11	15.39	126.3	1700	13.45 ± 0.33	15.40	127.8	1069	8.37 ± 0.26	15.39	126.3	769	6.09 ± 0.22
12	16.70	136.6	1664	12.19 ± 0.30	16.72	137.9	1060	7.69 ± 0.24	16.70	136.6	736	5.39 ± 0.19
13	17.99	146.0	1830	12.53 ± 0.29	18.03	146.1	1223	8.37 ± 0.24	17.99	146.0	788	5.49 ± 0.19
14	19.28	155.6	2085	13.40 ± 0.29	19.33	157.6	1318	8.36 ± 0.23	19.28	155.6	916	5.88 ± 0.19
15	20.56	164.9	2150	13.04 ± 0.28	20.63	166.9	1359	8.36 ± 0.22	20.56	164.9	842	5.11 ± 0.18
16	21.84	174.0	2114	12.15 ± 0.26	21.89	167.5	1331	7.95 ± 0.22	21.84	174.0	938	5.39 ± 0.18
17	23.10	184.1	2347	12.75 ± 0.26	23.12	177.9	1488	8.36 ± 0.22	23.10	184.1	1030	5.59 ± 0.17

[a] $r = \sqrt{r_1 r_2}$ (arcminutes).
[b] Area is square arcminutes.
[c] The estimated error is $\sqrt{n}$.
[d] Counts were made only in dust free regions and corrected as described in § II.

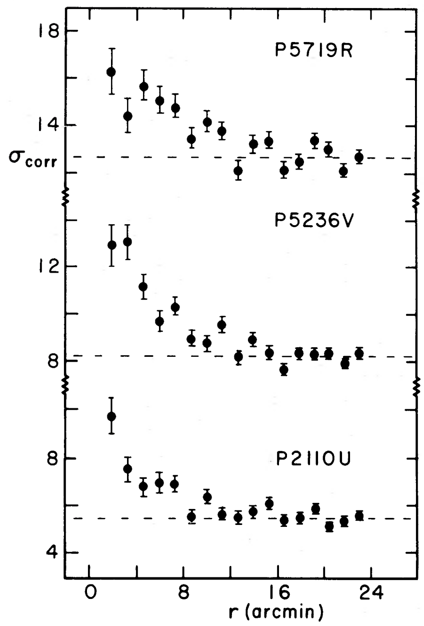

FIG. 2.—Surface density of objects per square arcmin, σ, plotted against the distance in arcmin from the center of NGC 5128 for all three plates. The dashed lines represent adopted background levels.

test the effect of differences in the assumed background, however, we defined a mean σ_b (i.e., background surface density) from counts in rings 9 to 17 (case 1) and rings 12 to 17 (case 2) on each plate. The adopted values for σ_b are given in Table 3; for all three plates the differences between case 1 and case 2 are of the order of the rms errors in σ_b. In the following discussion we have retained the two background values for each plate as a guide to the effect of uncertainties in σ_b on our estimate of clusters counted.

In addition to the difficulties in determining a satisfactory background density, we face the possibility of angular asymmetries in the counts around NGC 5128. HHBH and Evans and Harding (1961) both noted a clumpiness (i.e., small-scale variations) in their counts. This could be due to variations in foreground star densities or background galaxy clustering, as well as localized obscuration in the vicinity of NGC 5128 itself. We also noted substantial subsector to subsector differences in our counts and therefore endeavored to investigate this by examining the sector to sector (angular) differences in σ on all three of our plates. A sample of the result is shown in Figure 3 in which we plot $\langle\sigma\rangle$ vs. sector for the outer three rings (15 to 17). Again the error bars represent rms errors and the dashed line is the mean for each plate. Given the small data sample used to define each point it is difficult to attach great significance to the results of Figure 3. Certainly there are sector to sector variations, but in general there appears to be no trend common to all three plates. While it also appears that there may be some evidence for clumpiness in the star counts, it is random and cannot be removed systematically from the data. Only in the inner rings—which were not used to determine the background—does any nonrandom variation in σ with sector appear. This can be seen from Figure 4 in which σ is plotted against sector for the inner rings 3 to 8, whose area nearly equals that of rings 15 to 17. Here, the potential trend appears to be such that fewer objects were generally counted near the dust lane (though outside its obvious extent) than near the galactic poles. These results are comparable to the sector-to-sector variations in the Schmidt plate counts given by HHBH in their Table 11. Obviously the field is a difficult one in which to define the background level; but, because our apparent uncertainties seem to be of the order of the errors, further analysis is not justified.

TABLE 3

ADOPTED BACKGROUND DENSITIES (σ_b)

	P5719*R*	P5236*V*	P2110*U*
Case 1[a].........	12.76 ± 0.18	8.27 ± 0.11	5.55 ± 0.10
Case 2[b].........	12.68 ± 0.20	8.19 ± 0.12	5.46 ± 0.10

[a] σ_b is the mean surface density taken from rings 9–17.
[b] σ_b is taken from rings 12–17.

III. COUNT ANALYSIS—DETERMINATION OF N_{lim}

The total "cluster" population above the plate limit, N_{lim}, can be found in several ways, all of which have fundamental weaknesses. We used three methods in this investigation as

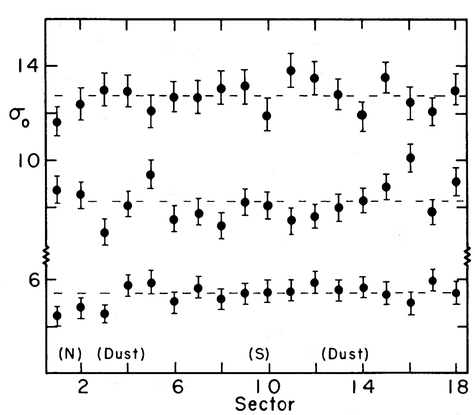

FIG. 3

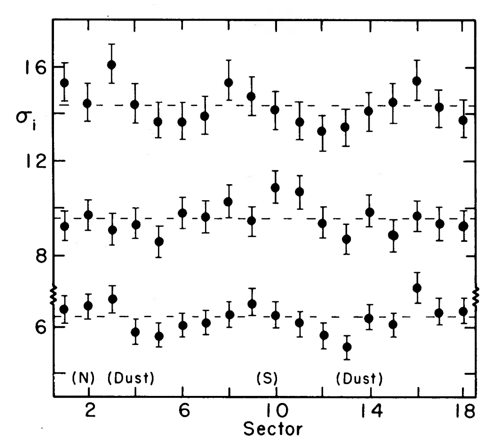

FIG. 4

FIG. 3.—Mean surface density, σ, for the outer region (rings 15–17) plotted against sector number. The orientation is such that north is approximately at the boundary between sectors 1 and 18, while the dust lane lies in sectors 3 to 4 and 12 to 13. Again, error bars represent rms errors.

FIG. 4.—Mean surface density, σ, for the inner counted region (rings 3–8) plotted against sector number as in Fig. 3.

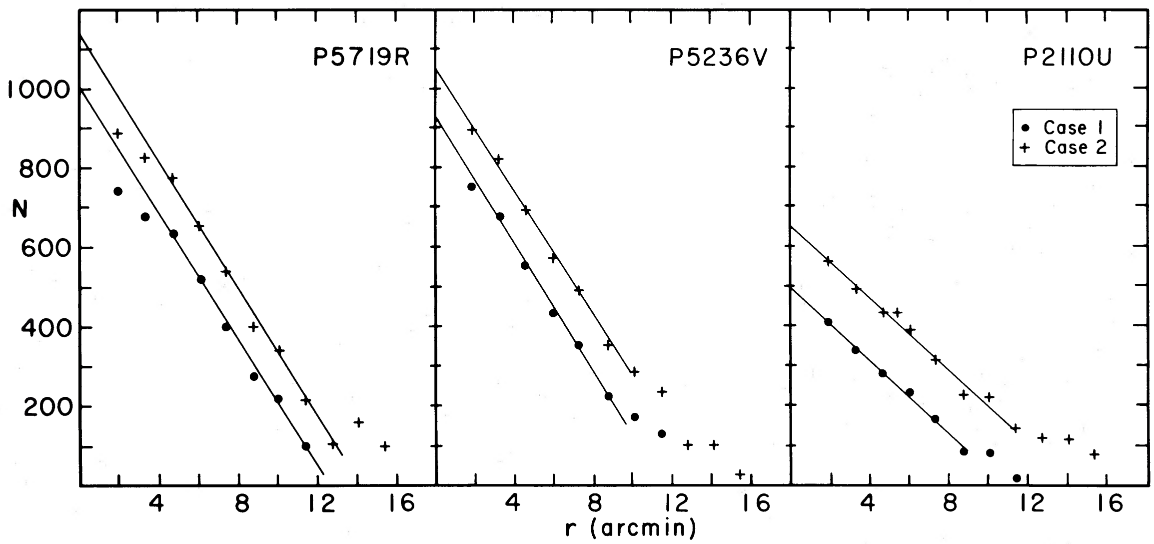

FIG. 5.—Excess number of objects above background for the two adopted background densities (i.e., case 1 and 2) on each plate. The cumulative number is plotted, counting inward to radius r; extrapolating to $r = 0$ gives an estimate of the total number of objects above the plate limit, $N_{\rm lim}$.

follows. (1) The total number of background objects in the counted area, N_b, was subtracted from the total number of counted objects, N_c, to give the number of counted objects in excess of background. (2) The same procedure as described in (1) was carried out, but for each individual ring. Then a cumulative total of excess objects was obtained and extrapolated linearly to $r = 0$ (see Fig. 5). (3) Based on the result of van den Bergh (1976) we fitted a de Vaucouleurs $r^{1/4}$ halo light distribution to the radial count distribution and calculated $N_{\rm lim}$ assuming the cluster and halo populations have the same radial distribution for the range $r = 0$ to $24'$. The results for the three methods are given in Table 4.

In method 1 the value obtained for $N_{\rm lim}$ is clearly a lower limit since it does not attempt to estimate the number of uncounted "clusters" in the center ring ($r < 1.4'$). It does, however, give specifically the total number of counted objects in excesss of the σ_b derived. Methods 2 and 3, on the other hand, attempt to estimate the number of "clusters" outside the counted region but must make untested assumptions to do so. For instance, our values for $N_{\rm lim}$ using the halo light distribution require the assumption that the $r^{1/4}$ law holds for $0 < r < 24'$ whereas, van den Bergh based his conclusions on data with $1' < r < 10'$. We also note that, while the radial distribution of some globular cluster systems matches the halo light in the outer regions (cf. Harris and van den Bergh 1981), there are also at least some galaxies in which the two systems differ: M87 (Harris and Racine 1979) and NGC 4472 (Harris and Petrie 1978; Harris and van den Bergh 1981). Finally, we note that there is no *a priori* justification for estimating $N_{\rm lim}$ by linear extrapolation; doing so is merely an attempt to use the observed data to estimate the central uncounted population.

The situation is considerably less clear for the innermost regions. We have no information, from studies of either our Galaxy or of other systems, which allows us to predict the radial distribution of globular clusters in the nucleus of a galaxy. Harris, Harris, and Harris (1984) have carried out star counts around NGC 4594 (the Sombrero) and find a deficiency of bright clusters relative to the halo light for $r < 2'$ (~ 8 kpc). Similar indications are present for the giant elliptical M87 (Racine 1976, unpublished). In both of these cases U plates were used to confirm results found in B, V, and R. Because the nuclear bulge of a galaxy tends to be redder than even red

TABLE 4
TOTAL CLUSTER POPULATION ABOVE PLATE LIMIT ($N_{\rm lim}$)

Method		P5719*R*	P5236*V*	P2110*U*
1. Counts in excess of σ_b	case 1	742 ± 115	751 ± 85	410 ± 70
(rings 1–*n*)	case 2	887 ± 191	895 ± 129	578 ± 106
i.e., $1\rlap{.}'38 < r < 12\rlap{.}'1$; $16\rlap{.}'1$				
2. Linear extrapolation	case 1	1000	940	500
$0 < r < 12\rlap{.}'1$; $16\rlap{.}'1$	case 2	1140	1050	655
3. Fit to halo light, $r^{1/4}$	$r = 0$ to ∞	1670	1670	1090
law[a] $0 < r < \infty$				
inner circle		296	296	192
($r < 1\rlap{.}'38$)				
rings 1–11		994	994	649
($1\rlap{.}'38 < r < 16\rlap{.}'1$)				
rings 12–17		130	130	85
($16\rlap{.}'1 < r < 23\rlap{.}'7$)				
rings 18–∞		250	250	164
($23\rlap{.}'7 < r < \infty$)				

[a] Neither case 1 or 2; σ_b redetermined—see § III.

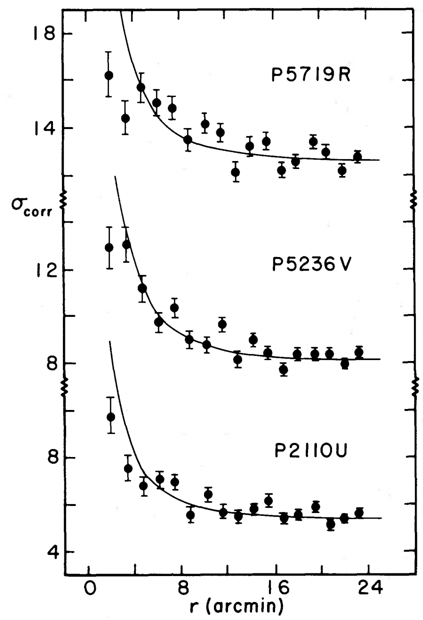

FIG. 6.—Surface density vs. r as in Fig. 2, but with van den Bergh's $r^{1/4}$ law for the halo light fitted to the observations (*solid line*).

globular clusters, the galaxy's surface brightness does not interfere with star counts as severely in U as in V or R until much closer to the center. We can see the relation between globular clusters and the surface brightness of NGC 5128 in Figure 6 where, for $r < 4'$, the surface density of our counts is already well below that expected from the halo light distribution on the R plate. By contrast, the U plate is beginning to drop slightly below the halo light curve only at $r \sim 2'$. Because our plates of NGC 5128 were too deep to allow counting at $r < 2'$, we cannot evaluate the legitimacy of using the halo light distribution in extrapolating our counts to $r = 0$ to determine $N_{\rm lim}$.

If we assume, as in method 3, that our counts *do* follow the observed halo light $r^{1/4}$ law found by van den Bergh (1976), the resulting curves appear to be systematically higher than the observations for the inner two rings (cf. Fig. 6). We should stress here that our subsequent remarks concerning the radial distribution of the counts refer specifically to a match with van den Bergh's observations of the NGC 5128 halo light distribution. In fact, an $r^{1/4}$ law can be fitted to our counts, even at small r, but with a flatter slope than van den Bergh's result. One obvious source of error in the fit which might cause a discrepancy between our counts and the observed halo light is an error in the adopted background surface density. We tested the effect of changes in σ_b by redetermining the fit to van den Bergh's $r^{1/4}$ law for two cases: (a) lowest—σ_b was assumed to be equal to the lowest σ observed on each plate (cf. Table 2); (b) highest—σ_b was assumed to be higher than the best fit value by $\sigma_{\rm best\,fit} - \sigma_{\rm lowest}$. The count data were again normalized to the halo light distribution by finding $N_{\rm lim}$ according to method 1 (i.e., the number of objects above background in the counted region) for each case. The resulting fits are shown in Figure 7, where it can be seen that the halo light curve is lowered for $r < 4'$ when σ_b is raised, and vice versa! This possibly surprising result comes about because we have forced our counts (obtained for $1'.4 < r < 23'.7$) to match van den Bergh's $r^{1/4}$ law (derived from observations with $1' < r < 10'$) with an effective radius of $r = 5'.5$. Thus changing σ_b does not result in a simple vertical shift in the derived curve. Note also that improving the match between the observational data and the halo light for $r < 4'$ results in a somewhat poorer match for large r. It appears, then, that if we wish to match the distribution of the NGC 5128 globular cluster system to the observed halo light we cannot necessarily call upon uncertainties in σ_b to resolve the problem.

Two other factors could explain our deficiency of clusters in the region $1'.4 < r < 4'$. (We did not count inside $1'.4$ because of the influence of light, and also because of obscuration, in much of that region, from the dust lane.) First, the background light of NGC 5128 at $1'.4 < r < 4'$ may still be high enough to affect the counting in that region. The background specular density is about 1.0 above clear plate at $r = 2'$ on P5236 and (although we have no measurements for it) the same appears to be true for P2110. Thus, at least for two of our plates, it seems unlikely that the density is high enough to interfere with the counts at radii in excess of $2'$. A second possibility is the presence of diffuse dust which could obscure at least some of the clusters on the far side of NGC 5128. Van den Bergh's photometry (1976, cf. his Figs. 4–6) shows almost no points with $B-V$ or $U-B$ redder than the general distribution by more than about 0.1 or 0.2 mag, or V fainter by more than 0.2 mag, outside the dust lane. In spite of the fact that the boundaries of the $2'$ wide dust lane have sharp edges, the increase in cluster density predicted by the halo light fit is not seen near those boundaries. On the other hand, discrete dust clouds are seen as far out as $4–5'$ from the dust lane. Perhaps individual small effects, when integrated over the entire line of sight, may prevent clusters on the far side from being counted.

The sum total of these effects is difficult to evaluate, and we are left, for the present, with only the tantalizing possibility that the NGC 5128 globular cluster system is deficient relative

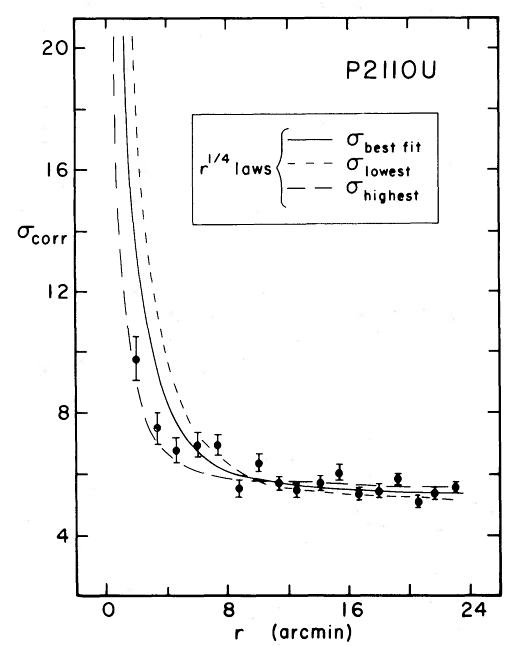

FIG. 7.—Surface density vs. r for P2110U with an $r^{1/4}$ law fitted as in Fig. 6. Here, in addition to the "best fit" curve, are shown fits using background values $\sigma_b = \sigma_{\rm lowest}$ (the lowest value of σ for the U plate) and $\sigma_b = \sigma_{\rm best\,fit} + (\sigma_{\rm best\,fit} - \sigma_{\rm lowest}) = \sigma_{\rm highest}$. Note that raising σ_b lowers the curve at small r and vice versa.

to the observed halo light distribution for $r < 4'$. If so, then using the halo light distribution to predict $N_{\rm lim}$ at small r will result in an overestimate.

IV. DETERMINATION OF THE TOTAL CLUSTER POPULATION, N_t

a) Estimates of Plate Limits, $m_{\rm lim}$

In spite of the difficulties in estimating a realistic $N_{\rm lim}$ from our counts, we feel that by using only the objects counted and ignoring the central region gives a legitimate lower bound. At the same time, matching an $r^{1/4}$ law is likely to give a reasonable upper bound. We can also see from Table 4 that, regardless of the method used, the values for $N_{\rm lim}$ are essentially the same for the V and R plates and substantially smaller in U. These differences are believed to be primarily the result of two factors: (a) differing limiting magnitudes for each plate and (b) differing absolute magnitudes of globular clusters in R, V, and U. However, by taking these effects into account, we should be able to use the information from all three sets of star counts to make an improved estimate of the total number of globular clusters, N_t, around NGC 5128.

As a first step, we estimated the limiting magnitude for each plate with the aid of a photoelectric *UBVRI* sequence in the field (McElroy and Humphreys 1982). For the V and R plates, secondary images of the sequence stars produced by the Pickering (1891)–Racine (1969) prism were combined with $\Delta m = 6.95$ (cf. HHBH and references therein) to give $R_{\rm lim} = 22.0$ and $V_{\rm lim} = 22.2$; both values are probably accurate to ± 0.25 mag. Since the U plate had no secondary images, we proceeded to determine its limiting magnitude by estimating U magnitudes for (a) HHBH clusters, based on a mean $(U-B)_0$ vs. $(B-V)_0$ relation for the Galactic globulars, and (b) secondary standards from HHBH calibrated plates, assuming them to be normal main-sequence stars. These procedures suggest $21.5 \leq U_{\rm lim} \leq 22.0$.

b) Determination of the Total Cluster Population, N_t

If we know the limiting magnitude of our plates and the distance to NGC 5128, we can then estimate what fraction of the total cluster population is detectable on our plates. Harris and Racine (1979) have found that the luminosity function for globular clusters in the Local Group can be represented by a Gaussian with its peak at $\langle M_V \rangle = -7.3 \pm 0.1$ and a dispersion $\sigma_V = 1.20 \pm 0.05$. Obviously some adjustment to $\langle M \rangle$ and σ_V must be made to apply this information to the U and R plates. Adopting standard globular cluster colors of $(U-B) = 0.08$, $(B-V) = 0.65$, and $(B-R) = 1.31$ [Strom *et al.* (1981), consistent with new photometry by Hanes and Brodie (1984) and Hamuy (1984)], we find $\langle M_U \rangle = -6.6$ and $\langle M_R \rangle = 8.0$. From the evidence (Harris and Racine 1979; Hanes 1977) that the value of $\sigma = 1.2$ also applies in B and J, we have used $\sigma_U = \sigma_V = \sigma_R = 1.2$.

Estimates of the total globular cluster population expected from our counts were then made for three distances compatible with the various determinations in the literature, e.g., $D = 3$ [de Vaucouleurs (1979, 1980), HHBH]; $D = 5$ [Burbidge and Burbidge (1959)]; $D = 8$ [Sandage and Tammann (1974), Richter and Huchtmeier (1983)]. We adopted $E(B-V) = 0.10$ (van den Bergh 1976) along with $A_V = 3.2\ E(B-V)$, $A_R = 2.4\ E(B-V)$, and $A_U = 4.9\ E(B-V)$ (cf. Schild 1977; Savage and Mathis 1979). In Table 5 the predicted cluster populations, N_t, for each color, distance, and method are given.

In Figure 8 these data are displayed in plots of N_t vs. distance in each color. Two points can be made immediately.

TABLE 5

PREDICTED TOTAL CLUSTER POPULATION (N_t)[a]

Plate	$D = 3$ Mpc	$D = 5$ Mpc	$D = 8$ Mpc
a. Based on $N_{\rm lim}$ from counts only—1'.38 < r < 16'.1			
R	909	1037	1531
V	960	1248	2304
U[b]	1009(796)	2289(1538)	10377(4817)
b. Based on $N_{\rm lim}$ from linear extrapolation—0 < r < 16'.1			
R	1168	1333	1968
V	1126	1464	2703
U[b]	1143(902)	2594(1743)	11760(5458)
c. Based on $N_{\rm lim}$ from halo fit—0 < r < ∞			
R	1711	1953	2883
V	1792	2328	4299
U[b]	1903(1502)	4317(2900)	19569(9083)

[a] Background σ_b is from case 2 only.

[b] Values in parentheses are for $U_{\rm lim} = 22.0$; the others are for $U_{\rm lim} = 21.5$.

First, $N_t \geq 900$ in all cases. Second, the V and R curves are very similar overall and virtually identical for distances of 3–4 Mpc. The two U curves intersect the V and R data in this same region, suggesting that our crude determinations of $U_{\rm lim}$ are not substantially in error. For all the methods the V and R curves are still similar at large distances while the U curves begin to diverge. The substantially greater sensitivity of the U counts is a consequence of combining three effects: the intrinsically fainter peak of the globular cluster luminosity function, the plate limit, and the larger ratio of total-to-selective absorption in U. As a result, while the R and V plates sample a large (and very similar) fraction of the assumed globular cluster population, the U plate reaches fainter than the peak of the cluster luminosity function *only* if the system is as close as 3 Mpc. Thus the prediction of N_t from the U plate is based on a counted sample of a much smaller portion of the luminosity function than is the case in V and R. Fortuitously, however, even the U plate samples more than 25% of the presumed cluster population at 5 Mpc and we consider intercomparison of the U, V, and R results to be legitimate.

The similarity between the three sets of curves in Figure 8 demonstrates the leverage of the U counts when combined with V or R data. Regardless of the method used to determine $N_{\rm lim}$, the distances derived are not significantly different. The probable value of N_t remains in the range ~1000 to 1800 (see Table 5). This range primarily reflects the differing areas over which the total population was determined in each method. Based on Figure 8 we conclude that $N_t \sim 1800$ for a distance of 3–4 Mpc for NGC 5128.

c) Effects of the Adopted Luminosity Function on N_t and D

Our star count results giving $D = 3$–4 Mpc for NGC 5128 are decidedly at the low end of the 3–8 Mpc range in the literature, and this result is essentially independent of the method we use to determine $N_{\rm lim}$. In order to make the star count data give $D > 5$ Mpc (and consequently $N_t \gg 2000$) we would need to assume that the luminosity function of the NGC 5128 globulars is significantly different from the Local Group one. If the mean colors or absolute magnitudes of the NGC 5128 globulars are significantly different from those of the Galactic globulars that dominate the Harris and Racine Local

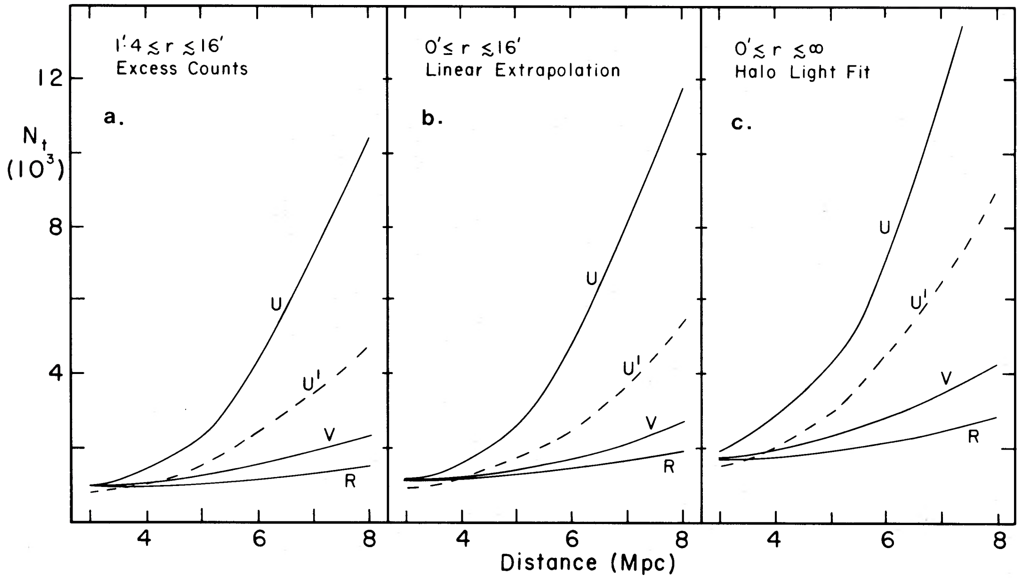

FIG. 8.—Total cluster population, N_t, plotted against the distance to NGC 5128 in Mpc based on the three methods of determining $N_{\rm lim}$. In each case the results are plotted for all three plates with two U curves for the limiting magnitude estimates. The solid line is for $U_{\rm lim} = 21.5$ and the dashed line for $U_{\rm lim} = 22.0$.

Group luminosity function, then the peak of the NGC 5128 luminosity function might be different. Such a possibility is suggested by the colors of the 19 confirmed clusters of HHBH which give $\langle B-V \rangle_0 = 0.81 \pm 0.03$ as compared with $\langle B-V \rangle_0 = 0.65 \pm 0.01$ for the Galactic globulars tabulated by Harris and Racine (1979). We can estimate the effect of having either a very blue or very red cluster population on the method of Figure 8 by assuming that the mean colors and absolute magnitudes of the NGC 5128 globulars are comparable to either the reddest $[(B-V)_0 = 0.89]$ or bluest $[(B-V)_0 = 0.60]$ ten Galactic globulars. For the reddest clusters this would then give $\langle M_R \rangle = -8.7$, $\langle M_V \rangle = -7.9$, and $\langle M_U \rangle = -6.6$, and for the bluest $\langle M_R \rangle = -7.9$, $\langle M_V \rangle = -7.3$, and $\langle M_U \rangle = -6.7$. (Note that, although the peak absolute magnitudes in V and R change substantially, $\langle M_U \rangle$ is almost constant.) We can also examine the effect on Figure 8 of changing the dispersion of the luminosity function from 1.2 to 1.4. Using these new parameters we determined N_t as before and the resulting plots of N_t vs. distance were quite similar to Figure 8 in predictions of *both* N_t and distance. In all cases we used the intermediate values for $N_{\rm lim}$ as given by method 2. For the bluest clusters, the curves were almost identical to Figure 8*b*. For the reddest clusters, the V and R curves were almost flat, an indicator that if the NGC 5128 globular cluster system is ~ 0.15 mag redder than the Local Group one our plates have sampled a very high fraction of the population even at 8 Mpc. Changing to 1.4 altered the V and R curves very little and lowered the U curves slightly, thus increasing the acceptable distance range to ~ 4.5 Mpc—again a reflection of the change in sampling at the different wavelengths. Thus little difference in estimated values of N_t or galactic distance is produced by assuming that the NGC 5128 globulars are more appropriately compared with very blue or very red Galactic globulars or that σ_V is larger. This is particularly interesting since Frogel (1984) has recently observed 12 HHBH clusters in the infrared and finds them to be much like old Galactic globulars, not like the intermediate-age Magellanic Cloud clusters. Presumably, then, using Galactic globular cluster characteristics to interpret our counts is entirely reasonable.

In our analysis of the total cluster population we have made assumptions about its radial distribution as described in terms of the three methods of determining $N_{\rm lim}$. The presentation of σ vs. r in Figure 6 suggests that the data fit an $r^{1/4}$ law in the outer regions but may fall below the halo light distribution for small r. In Figures 9 and 10 we present the radial distribution in logarithmic form with log σ_{cl} plotted against log r (Fig. 9) and $r^{1/4}$ (Fig. 10). In Figure 9 the three plates give about the

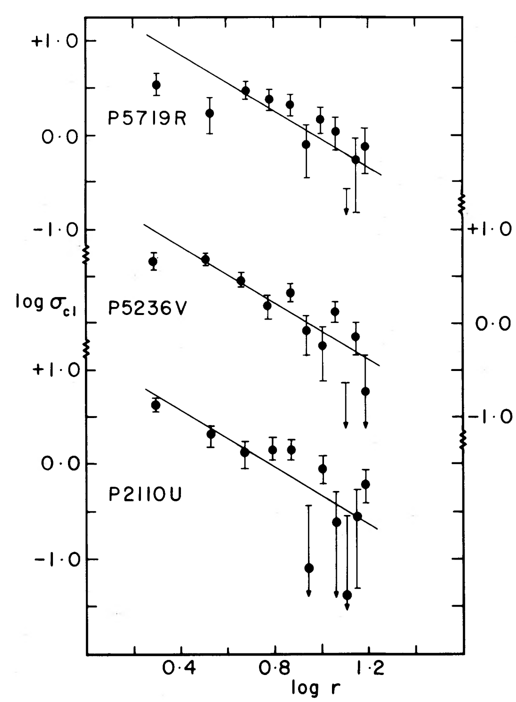

FIG. 9.—Logarithm of the excess surface density above background, σ_{cl}, plotted against the log of the radial distance from the center of NGC 5128 (in arcmin) for the three plates. The case 2 (see § II) background was assumed. The lines show a power law with a slope of -1.5.

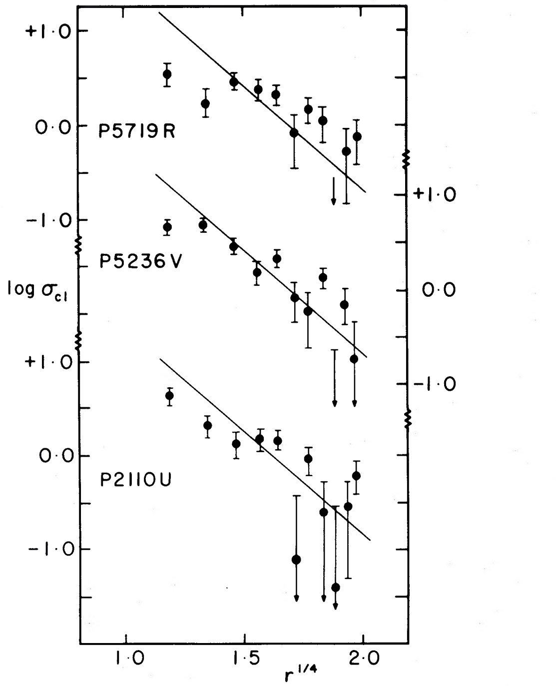

FIG. 10.—Log σ_{cl} as in Fig. 9 plotted against $r^{1/4}$ (in arcmin). The lines show a de Vaucouleurs law with $r_e = 5'.5$ (found for the halo light by van den Bergh) scaled to fit the observed total excess in rings 1–11.

same slope suggesting a power law with a slope of -1.5, similar to results found for NGC 3311 (Harris, Smith, and Myra 1983), M87 (Harris and Smith 1976), and M49 (Harris and Petrie 1978). As already discussed our results also are in agreement with an $r^{1/4}$ law distribution for $r > 4'$, but we are unable to distinguish between the two with the data at hand.

V. THE LUMINOSITY FUNCTION AND SPECIFIC FREQUENCY OF THE CLUSTER SYSTEM

Data can now be combined from several sources to investigate the luminosity function of the globular cluster system over a range of 5 mag, a larger range of luminosity than has previously been possible for any elliptical galaxy. Twenty clusters confirmed by velocities give a lower limit to the bright end of the luminosity function (HHBH) at $V \sim 17$ to 18. Photometry of a large, complete sample of images (HHHM) gives useful points at $V = 19$ and $V = 20$. Earlier counts of film copies of U.K. Schmidt plates (BHH, HHBH) give points at $J \sim 22$, equivalent to $V \sim 21.5$ for clusters in NGC 5128, and the present paper gives the deepest available counts at $V = 22.2$.

For intercomparison, the counts must all be normalized to the same area in NGC 5128. In order to minimize the possible errors introduced by assumptions about how the clusters are distributed in NGC 5128, we have *not* normalized the counts to give the total population. Instead, we refer to the area $1'.4 \leq r \leq 16'.1$ counted in this paper, which omits three of the 20 confirmed clusters that lie outside this region. The counts are scaled up as follows: HHHM ($1'.9$ to $15'.8$) by 1.10, BHH ($3'.4$ to $14'.5$) by 1.55, and HHBH ($3'.8$ to $16'.0$) by 1.64. These factors are correct if the cluster distribution matches the halo light, and should be nearly correct for any reasonable case. Each error bar has also been scaled by the same factor.

The luminosity function is shown in Figure 11*a* and *b*. In Figure 11*a* we compare it with the Local Group luminosity function ($\langle M_v \rangle = -7.3$, $\sigma_v = 1.2$) if $D = 3.3$ Mpc, $E(B-V) = 0.10$, and $N = 1000$ total clusters are projected within the counted region. The fit to the data is remarkably good. It demonstrates that if the distance to NGC 5128 is about 3 or 4 Mpc, then its cluster luminosity function appears to be normal. Two other fits are also shown that are in marginal agreement with the data (i.e., $D = 2.6$, $N = 600$ and $D = 4.2$, $N = 1500$). These show that if the distance is in fact larger than

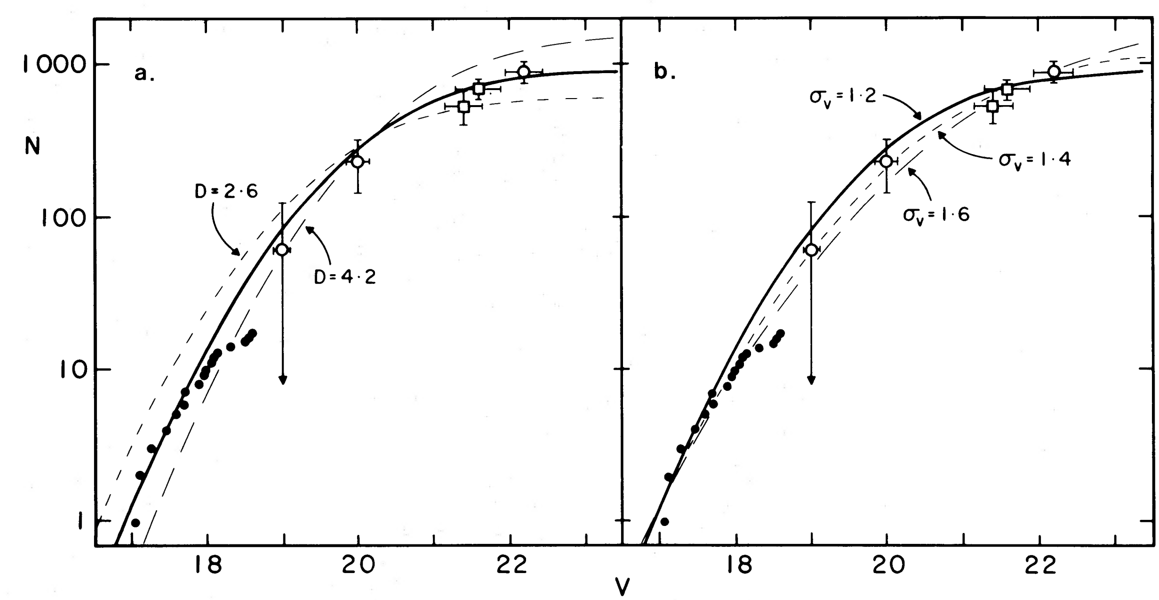

FIG. 11.—The cumulative luminosity function of clusters in the region $1'.4 < r < 16'.1$. The solid dots show confirmed clusters, but are increasingly incomplete for $V > 18$. The squares show counts from earlier papers. In (*a*), the solid line shows a Local Group luminosity function (with $\sigma_V = 1.2$ mag) for a distance to NGC 5128 of 3.3 Mpc. The dashed lines show fits for distances of 2.6 Mpc and 4.2 Mpc. In (*b*) the dashed lines show Gaussian luminosity functions with $\sigma_V = 1.3$ and 1.4 (see § V).

TABLE 6

DISTANCE AND SPECIFIC FREQUENCY OF THE NGC 5128 CLUSTER SYSTEM

σ_V[a]	Distance (Mpc)	M_V	N[b]	N_t	S
1.2	2.6	−21.19	600	1000	3.4
	2.9	−21.43	770	1200	3.2
	3.3	−21.71	900	1500	3.1
	3.8	−22.02	1150	1900	3.0
	4.2	−22.24	1500	2500	3.2
1.4	4.6	−22.43	1200	2000	2.1
1.6	6.5	−23.18	1700	2900	1.5

[a] $\sigma_V = 1.2$ for the Local Group cluster luminosity function.
[b] N = total clusters projected within the counted region.

4.5 Mpc, then the cluster luminosity function in NGC 5128 must be different from that in the Local Group.

We can now calculate the specific frequency (i.e., number of clusters per unit halo light): $S = N_t \times 10^{-0.4(M_v+15)}$, where M_v is the integrated magnitude of the galaxy's spheroidal component. (cf. Harris and van den Bergh 1981). The values for S given in Table 6 were based on $V = 6.2$ and $E_{B-V} = 0.10$ (van den Bergh 1976) and values of N_t derived from scaling up the luminosity function best fit by a factor of 1.68. This factor assumes 59.5% of the clusters lie in the counted region $1\farcm4 < r < 16\farcm1$ in accordance with the halo light distribution. For the Local Group luminosity function the S values are slightly below the usual range for elliptical galaxies, of $4 \lesssim S \lesssim 10$ (Harris and van den Bergh 1981); these values suggest that NGC 5128 possesses a globular cluster population similar to but slightly smaller than that of normal ellipticals.

If, as noted above, the distance to NGC 5128 is in fact larger than ~4.5 Mpc, then Figure 11*a* shows that its globular clusters must follow a different luminosity function. Figure 11*b* shows fits to the data for Gaussian distributions with σ_V increased to 1.4 and to 1.6 mag. These functions fit the data as well as the Local Group function, and they naturally predict larger total cluster populations but smaller values of S, as given in Table 6. Of course, once the assumption of the Local Group luminosity function is dropped, there is little reason to expect the magnitude of the peak to stay fixed at $M_v = -7.3$, or to expect a Gaussian distribution at all. Without knowing the explicit form of the luminosity function, we can only place constraints on N_t and S. The curves in Figure 11*b* and the nonstandard values in Table 6 should not be considered as anything more than possible representations. Values of σ_V larger than about 1.3 are inconsistent with clusters in Local Group galaxies (Harris and Racine 1979), and values larger than about 1.4 are unlikely in Virgo elliptical galaxies (Hanes 1983). The evidence from the various Local Group galaxies that the globular cluster luminosity function is universal is, to us, quite compelling. While a different function such as a Gaussian with $\sigma_V = 1.4$ cannot be ruled out for NGC 5128, we believe that present evidence favors the Local Group function and the fits shown in Figure 11*a*.

VI. CONCLUSIONS

It now appears from the star counts presented here that NGC 5128 possesses a globular cluster system that, while small, is near the normal range for an elliptical galaxy. These data are combined with other counts to brighter limiting magnitudes, and with the firm lower limit to the bright tail of the luminosity function established by spectroscopically confirmed clusters. For a distance of 3 to 4 Mpc, the cluster luminosity function agrees well with the Local Group luminosity function over a range of 5—a larger range than has been studied in any other elliptical galaxy. This agreement indicates that the luminosity function is, in fact, similar to that in the Local Group. Our best results suggest that $1200 \lesssim N_t \lesssim 1900$ for a distance of 2.9 to 3.8 Mpc, giving a specific frequency of $3.0 \lesssim S \lesssim 3.2$. If, as permitted by the data, we increase the dispersion of the luminosity function from 1.2 to 1.4, then $N_t \sim 2000$ for a distance of 4.6 Mpc.

The radial distribution of the star counts in the outer regions seems to fit a de Vaucouleurs $r^{1/4}$ law, as does the halo light. The situation in the center of the galaxy is less clear: for $r < 4'$ there may be a deficiency of clusters relative to the halo light.

Since the U color provides such a crucially informative comparison with the data in V and R, it would be worthwhile to obtain improved estimates of the limiting magnitude for all three plates. These might suitably be obtained from CCD frames in U, V, and R in the field of the plates.

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REFERENCES

Burbidge, E. M., and Burbidge, G. 1959, *Ap. J.*, **129**, 271.
Chiu, L.-T. G. 1976, *P.A.S.P.*, **88**, 803.
de Vaucouleurs, G. 1979, *A.J.*, **84**, 1270.
———. 1980, *Ap. J. (Letters)*, **240**, L93.
Ebneter, K., and Balick, B. 1983, *P.A.S.P.*, **95**, 675.
Evans, D. S., and Harding, G. A. 1961, *M.N. Astr. Soc. S. Africa*, **20**, 65.
Frogel, J. A. 1984, *Ap. J.*, **278**, 119.
Graham, J. A., and Phillips, M. M. 1980, *Ap. J. (Letters)*, **239**, L97 (GP).
Hamuy, M. 1984, submitted to *Astr. Ap. Suppl.*
Hanes, D. A. 1977, *M.N.R.A.S.*, **180**, 309.
———. 1983, *Highlights of Astronomy*, **6**, 227.
Hanes, D. A., and Brodie, J. P. 1984, submitted to *M.N.R.A.S.*
Harris, H. C., Harris, G. L. H., Hesser, J. E., and MacGillivray, H. T. 1984, *Ap. J.*, **287**, 185 (HHHM).
Harris, W. E., Harris, H. C., and Harris, G. L. H. 1984, *A.J.*, **89**, 216.
Harris, W. E., and Petrie, P. L. 1978, *Ap. J.*, **223**, 88.
Harris, W. E., and Racine, R. 1979, *Ann. Rev. Astr. Ap.*, **17**, 241.
Harris, W. E., and Smith, M. G. 1976, *Ap. J.*, **207**, 1036.
———. 1981, *A.J.*, **86**, 90.
Harris, W. E., Smith, M. G., and Myra, E. S. 1983, *Ap. J.*, **272**, 456.
Harris, W. E., and van den Bergh, S. 1981, *A.J.*, **86**, 1627.
Hesser, J. E., Harris, H. C., van den Bergh, S., and Harris, G. L. H. 1984, *Ap. J.*, **276**, 491 (HHBH).
McElroy, D. B., and Humphreys, R. M. 1982, *P.A.S.P.*, **94**, 828.
Pickering, E. 1981, *Harvard Annals*, **26**, 14.
Racine, R. 1969, *A.J.*, **74**, 1013.
Richter, O.-G., and Huchtmeier, W. K. 1983, preprint.
Sandage, A. R., and Tammann, G. A. 1974, *Ap. J.*, **194**, 559.
Savage, B. D., and Mathis, J. S. 1979, *Ann. Rev. Astr. Ap.*, **17**, 73.
Schild, R. E. 1977, *A.J.*, **82**, 337.

Sersic, J. L. 1960, *Zs. Ap.*, **51**, 64.
Strom, S. E., Forte, J. C., Harris, W. E., Strom, K. M., Wells, D. C., and Smith, M. G. 1981, *Ap. J.*, **245**, 416.
Tremaine, S. D. 1976, *Ap. J.*, **203**, 345.
Tremaine, S. D., Ostriker, J. P., and Spitzer, L. Jr. 1975, *Ap. J.*, **196**, 407.
van den Bergh, S. 1976, *Ap. J.*, **208**, 673.
———. 1979, *P.A.S.P.*, **91**, 639.
van den Bergh, S., Hesser, J. E., and Harris, G. L. H. 1981, *A.J.*, **86**, 24 (BHH).

P. J. Curry: 4033 Cedar Hill Rd., Victoria, B.C. V8N 4M9, Canada

G. L. H. Harris: Physics Department, University of Waterloo, Waterloo, ON N2L 3G1, Canada

H. C. Harris and J. E. Hesser: Dominion Astrophysical Observatory, 5071 W. Saanich Rd., Victoria, B.C. V8X 4M1, Canada