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RADIAL DISTRIBUTION AND TOTAL NUMBER OF GLOBULAR CLUSTERS IN M104

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Stellar images around M104 fainter than a threshold magnitude are concentrated toward the nucleus, thus they are certainly globular clusters associated with M104. By counting their images, the radial distribution of their projected number density is found to be similar to the luminosity profile of the spheroidal central bulge and can be represented by de Vaucouleurs' "1/4-law". The total number of globular clusters in M104 is estimated to be $(2.0^{+3.5}_{-1.0}) \times 10^3$.

Key words: globular clusters—spiral galaxies—spheroidal central bulge

I. Introduction

Globular clusters in external galaxies beyond the Local Group cannot be identified individually but can be recognized as a concentration of faint stellar images toward the nucleus. Both in elliptical and early-type edge-on spiral galaxies, globular clusters are conspicuously projected against faint featureless halos or spheroidal central bulges, whereas those in late-type face-on spiral galaxies are confused with numerous underlying supergiant stars or open clusters. The best example of the former case is the Sombrero, M104 = NGC 4594. In this paper, we count the faint stellar images around M104 in order to know the radial distribution of globular clusters around the nucleus and their total number. The photograph inspected in the present study (supplied by Caltech Bookstore) is a positive transparent copy reproduced from the plate taken with the Hale telescope as was done in *The Hubble Atlas of Galaxies* (Sandage 1961: hereinafter abbreviated as the *Atlas*). The results obtained in this paper for M104 will be used in a forthcoming paper (Wakamatsu 1977) as part of the data used to examine the correlation between the total number of globular clusters and the absolute luminosity of the spheroidal systems of the parent galaxies.

II. Radial Distribution

According to the *Atlas*, the original plate (PH-96-MH) was exposed for 30 minutes on a 103a-O plate without a filter. The scale of the transparent copy was measured by comparing it with the plate taken with the 188-cm telescope at the Okayama Astrophysical Observatory, and is found to be $2''.58$ mm^{-1}. The area of the reproduced field is $9'.7 \times 7'.6$, which is larger by approximately 25% than the area $9'.0 \times 6'.6$, of the photograph in the *Atlas*. On the transparent copy, numerous faint stellar images and diffuse ones (probably underlying distant galaxies) that were lost in the *Atlas* can be seen, thus the total calculated stellar images on it are approximately twice as numerous as those on the *Atlas*.

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At a glance, the globular cluster system of M104 is found to be somewhat flattened in the direction of its rotational axis, as in our Galaxy (Arp 1965) or in M31 (Sharov 1968). Its apparent axial ratio appears to be close to the value $b/a = 0.63$, i.e., the axial ratio derived from the luminosity profile of its spheroidal central bulge measured by van Houten (1961). Hence, in the following, $\sigma_{ap}(a)$, the projected number density of faint stellar images, is calculated for concentric elliptical shells each centered at the nucleus with the same axial ratio $b/a = 0.63$. The stellar images fainter than a threshold magnitude appear to be distributed around the nucleus with concentration toward it. All such stellar images are picked up. The adopted threshold images are such ones as located at $x = 65$ mm, $y = 158$ mm or $x = 187$ mm, $y = 31$ mm, measured from the lower-left corner of the photograph in the *Atlas*. With this procedure, it is found that for about 10% of the faint stellar images it is uncertain whether they are really stellar images or an irregularity of the emulsion. These are treated with half weight. The number of faint stellar images lying in each elliptical shell is counted, and the number is tabulated in column (4) of Table I. In column (3), the areas of the shells are presented. An asterisk means that a part of the shell is out of the rectangular area of the transparent copy. The values of $\sigma_{ap}(a)$ are listed in column (5).

The apparent number density $\sigma_{ap}(a)$ is plotted in Figure 1 against a, the semimajor axis of the ellipse. In the inner region, $\sigma_{ap}(a)$ decreases rapidly with the decrease of a, probably because detection of faint stellar images near the nucleus is severely disturbed by the luminous background light of the spheroidal central bulge. Indeed, the surface luminosity of the bulge at $a = 2'.6$ is $B = 21.7/\square''$, according to van Houten (1961). In the outer region, $\sigma_{ap}(a)$ decreases gradually with the increase of radius a even to the outermost limit that we have measured. In this way, the distribu-

TABLE I

Observational Data

Shell number†	Semi-major axis (arc min)	Area of shell (sq. min)	Number of faint images	$\sigma_{ap}(a)$ (objs/□')	$\sigma_{GC}(a)$ (objs/□')	Number of foreground stars	Number density (objs/□')
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	0.64	1.09	0	0	0	0	0
2	1.07	1.82	3.0	1.65	0	0	0
3	1.50	2.55	18.0	7.05	5.05	1	0.39
4	1.93	3.28	22.5	6.86	4.86	3	0.92
5	2.36	4.01	40.5	10.1	8.10	5	1.2
6	2.79	4.74	54.0	11.4	9.4	2	0.42
7	3.22	5.47	44.5	8.14	6.14	2	0.37
8	3.65	6.20	42.0	6.78	4.78	5	0.81
9	4.08	6.93	44.5	6.43	4.43	4	0.58
10	4.51	7.66	39.0	5.10	3.10	8	1.0
11	4.94	7.45*	36.0	4.84	2.84	2	0.27
12	5.36	6.59*	23.5	3.57	1.57	3	0.46
13	5.79	5.93*	21.0	3.54	1.54	2	0.34
14	6.22	4.49*	19.5	4.34	2.34	2	0.45
15	6.65	2.76*	7.5	2.71	0.71	1	0.36
16	7.08	1.54*	6.5	4.21	2.21	1	0.65
Total	--	72.51	422.0	--	--	41	--

† Shell number n represents an elliptical shell of semi-major axes from $a_1 = 0.429n$ to $a_2 = 0.429(n + 1)$.

tion of stellar images fainter than the threshold is found to show a clear concentration toward the nucleus. For the stellar images brighter than the threshold but fainter than such an image as that located at $x = 220$ mm, $y = 174$ mm in the *Atlas*, the number density is examined in the same procedure as described above. The result is tabulated in columns (7) and (8) of Table I and is shown in Figure 2. As expected, no clear concentration toward the nucleus is detected, implying that the threshold adopted above is appropriate for the purpose and that the faint stellar images thus picked up are really associated with the spheroidal system of M104.

At a sufficiently large radius, $\sigma_{ap}(a)$ gradually approaches an asymptotic value σ_{FG}, i.e., the number density of the foreground stars in the magnitude range considered here. From Figure 1, its upper limit can be determined: $\sigma_{FG} < 3.0/\square'$. It will be reasonable to take $\sigma_{FG} = 2.0 \pm 0.5/\square'$, which is the value obtained by Racine (1968) for the sky around M87. The reason is that the slightly larger image size of the plate of M104 than that of M87, when compared with the photographs in the *Atlas* taken with the similar emulsion and for the same exposure time, decreases the detec-

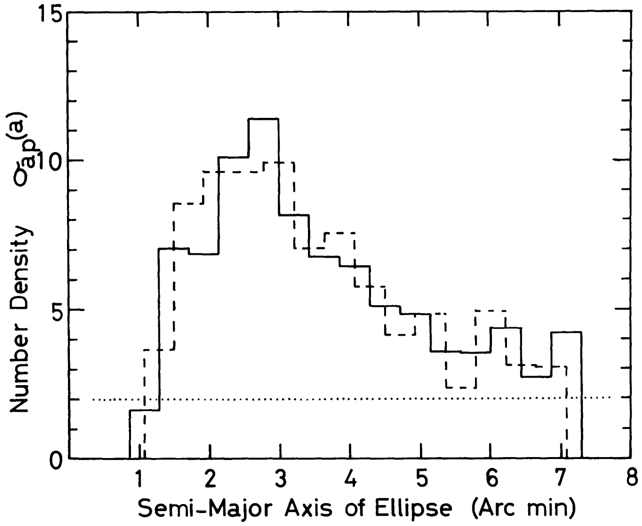

FIG. 1—Projected number density of faint stellar images $\sigma_{ap}(a)$, lying in each elliptical shell with an axial ratio of 0.63, is plotted against a, the semimajor axis of the ellipse with an interval of 0'.43. Full line refers to the result presented in column (5) of Table I, and broken line refers to the count made in intervals shifted over 0'.215. Dotted line represents σ_{FG}, the adopted number density of foreground stars.

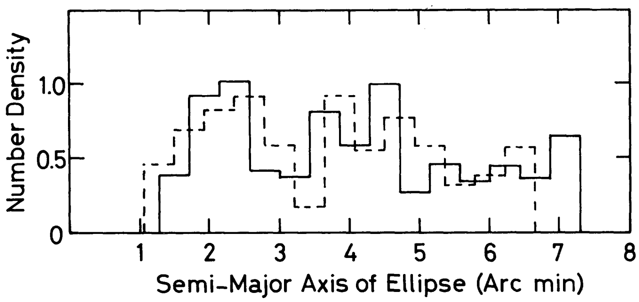

FIG. 2—Projected number density of faint stellar images which are slightly brighter than the images examined in Figure 1. Full line refers to the result presented in column (8) of Table I, and broken line refers to the count made in intervals shifted over 0'.215.

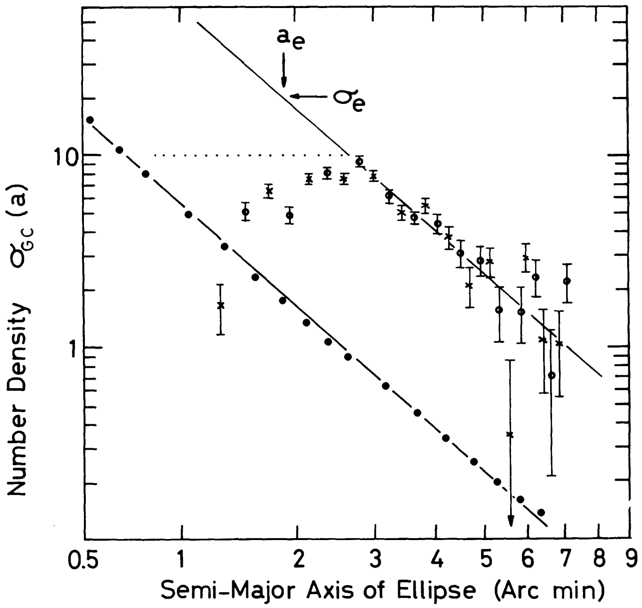

FIG. 3—Projected number density of globular clusters $\sigma_{GC}(a)$ (column (6) of Table I) is plotted against 1/4-power of a, the semimajor axis of the ellipse. Error bars represent the uncertainty introduced from that of the value σ_{FG}. Filled circles represent the luminosity profile of the spheroidal central bulge measured by van Houten (1961) in an arbitrary unit.

table number of faint foreground stars, while the difference in galactic coordinates between M104 (ℓ = 298°, b = 51°) and M87 (ℓ = 284°, b = 74°) acts to increase the value. These two factors may approximately cancel each other.

By subtracting σ_{FG} from $\sigma_{ap}(a)$, the projected number density of globular clusters in M104, i.e., $\sigma_{GC}(a)$, is obtained and is presented in column (6) of Table I. The density is plotted in Figure 3 against $a^{1/4}$. On this diagram, $\sigma_{GC}(a)$ can be approximated by a straight line at least in the outer region, hence the radial distribution of globular clusters follows de Vaucouleurs' (1962) "1/4-law", i.e.,

$$\log [\sigma_{GC}(a)/\sigma_e] = -3.33[(a/a_e)^{1/4} - 1] \quad ,$$

where a_e is the effective radius within which one-half of the total number of clusters are contained and σ_e is $\sigma_{GC}(a_e)$. From eye estimation, values of the parameters are $\sigma_e = 21/\square'$ and $a_e = 1'.9$.

For the sake of comparison, the surface luminosity profile along the minor axis of the spheroidal central bulge of M104, measured by van Houten (1961), is plotted in Figure 3 after scaling it to the major axis. As can be seen from Figure 3, the luminosity distribution can be well represented by a "1/4-law", and the slope is quite similar to that for the globular cluster, although the slope for the clusters cannot be determined precisely due to the scatters of the observed points and to the ambiguity in σ_{FG}. Therefore, the form of the radial distribution of globular clusters in the outer region coincides well with the luminosity profile of the spheroidal central bulge just beyond Holmberg's (1958) radius a_{Hol} = 6'.0. A similar result was obtained for M87 (Harris and Smith 1976). This fact may be one of the important clues for an understanding of the formation of spheroidal bulges and disks of spiral galaxies.

III. Total Number of Globular Clusters

If the distribution of globular clusters determined in the previous section can be extrapolated to the entire region around M104, then the total number of clusters within the magnitude range examined above amounts to 1100, within an uncertainty of at most 5%, which may be introduced from the uncertainty of the value σ_{FG}. This estimate seems to provide a maximum value, because the radial distribution $\sigma_{GC}(a)$ in the inner region may be thought to increase much more gradually with the decrease of a than to follow the "1/4-law". For the estimate of its minimum value, $\sigma_{GC}(a)$ is assumed to be $10.0/\square'$ within $a < 2\overset{'}{.}7$, as is shown in Figure 3, and the minimum number of clusters then amounts to 560. The true value may lie near the mean of the two extreme values, so we adopt 830 ± 270.

To evaluate the total number of clusters, we must carefully estimate the number of clusters fainter than our plate limit, by considering their luminosity function. The brightest clusters are clearly recorded on the blue print of the Palomar Sky Survey whose limiting magnitude for the declination zone of M104 ($\delta = -11°$) is about $m_{pg} = 20.6$ (Minkowski and Abell 1963), so Sandage's (1961) estimate for them, $m_{pg} = 20$, seems to be appropriate. The limiting magnitude of our plate, having somewhat large image sizes probably due to low altitude at Palomar Mountain, is slightly worse as compared with that taken in the best condition, so the magnitude range of globular clusters studied here is about 2.5 ± 0.5. Hence, the globular clusters examined above account for only $40^{+17}_{-20}\%$ of the total clusters, if the luminosity function is assumed to be similar to that of M31 (van den Bergh 1969). The total number of globular clusters can be evaluated to be $(2.0^{+3.5}_{-1.0}) \times 10^3$, by multiplying the value 830 ± 270 by a factor of $2.5^{+2.5}_{-0.75}$.

IV. Concluding Remarks

On our positive transparency, about 40 faint objects of nonstellar appearance can be seen. Van den Bergh (1976) commented, however, that many objects near M104 on the plates taken by 4-m telescopes at KPNO and CTIO are fuzzy, so they may be background galaxies rather than globular clusters. When our positive transparency is examined more closely, the distribution of the counted stellar images are more centrally concentrated in the N-E and S-W quadrants than in the N-W and S-E ones. Moreover, relatively bright stellar images among them are more populated in the N-E and S-W quadrants than in the N-W and S-E ones, although the total counted number in each quadrant differs slightly from each other. These asymmetries may be caused partly by misidentification of fuzzy images as stellar of appearance owing to deterioration of the image quality of our positive transparency in the reproducing process. This contamination problem, as discussed by Dawe and Dickens (1976) for the case of NGC 1399, is quite difficult to solve. Thus before regarding our results concerning the radial density distribution of globular clusters as definite, further observational studies are necessary in order to discriminate globular clusters from background galaxies by using differences of their image sizes and especially of their colors.

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