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THE EXPECTED NUMBER DENSITY OF GLOBULAR CLUSTERS NEAR THE GALACTIC CENTER

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ABSTRACT

Estimates are given of the distribution of globular clusters in the central region of the Galaxy. They are based partly on the assumption that the cluster distribution is identical with that of the RR Lyrae variables, on which we have better information. Within 1 or 2 kpc from the center, where direct observations are invalidated by absorption, the run of the density is computed from the gravitational field derived from the rotation of the H I nuclear disk combined with a Maxwellian cluster-velocity distribution. The resulting *initial* density of the clusters as a function of distance R from the center is shown in Figure 1. For $R < 1$ kpc the *present* density has been greatly reduced by dynamical friction, as discussed by Tremaine *et al.* The numbers remaining after account has been taken of this effect are given in Tables 1 and 2. The mass accumulated around the nucleus by the dynamical capturing is found to be about $2 \times 10^7\, M_\odot$, with an estimated uncertainty of a factor of 2.
Subject headings: clusters: globular — galaxies: Milky Way — galaxies: nuclei — X-rays: sources

I. SPACE DENSITIES

In connection both with the observations of X-ray sources in globular clusters and with the unidentified galactic center sources, it is of some importance to have an estimate of the number of globular clusters per unit area near the galactic center. This cannot at present be found from direct observations, because at latitudes below about 3° the extinction is so strong that even objects of such extreme intrinsic brightness as globular clusters have escaped detection. The effect of the extinction can clearly be seen in plots of the known globular clusters (see Arp 1965, Figs. 2, 3; Harris 1976, Fig. 1).

A careful analysis of the space distribution has recently been given by Harris (1976). He found that between $R = 3$ and 30 kpc from the center the distribution of clusters is remarkably isotropic and that the density $\nu(R)$ is roughly proportional to $R^{-3.5}$. Inside $R \approx 10$ kpc, $R^{-3.0}$ may give a somewhat better fit. Because of the evident incompleteness of low-latitude clusters beyond the center, the densities were computed from the clusters on our side of the center. The distance to the center was taken to be 8.5 kpc. The same value has been used throughout this *Letter*.

Harris's space densities for the region within $R = 10$ kpc are shown in the lower right corner of Figure 1. The vertical lines in the figure indicate the statistical mean-square errors.

In order to extrapolate these densities to smaller values of R, I have compared them with the density distribution of the RR Lyrae variables in the central region. Because of the common occurrence of the RR Lyrae stars in globular clusters and their similar velocity distribution, it is not unreasonable to suppose that they have the same space distribution, in particular in the central region, where this has been extensively investigated (see Oort and Plaut 1975). It was found that within $R = 5$ kpc their distribution is almost spherical, and that their density varies as R^{-3} between 1 and 5 kpc. At $R = 3$ it is roughly 30 kpc^{-3} (as against 0.07 for the clusters). With their aid we can extrapolate the cluster densities to about $R = 1.0$ kpc, as is indicated in Figure 1. The slope of the density curve for the RR Lyrae variables is seen to fit quite well with that for the clusters.

If we knew the velocity distribution, the density distribution could be extrapolated further inward by making use of the data on the gravitational field furnished by the rotation of the H I nuclear disk, the infrared radiation, and the light distribution in the nucleus of M31 (for a review, see Oort 1977). Using a spherical approximation, we find the potential Φ to vary linearly with $\log R$ between 80 and 1000 pc. If Φ is expressed in km s^{-1} and R in pc, $\Phi(R) - \Phi(0) = -54{,}000 + 120{,}000 \log R$.

About the velocity distribution of RR Lyrae variables close to the center little or nothing is known in a direct way. We do, however, possess velocity data for planetary nebulae, which in the nuclear region may belong to the same population type as the halo RR Lyrae variables and the globular clusters.

Radial velocities are known for 64 nebulae within about 0.7 kpc from the center. These were found to fit closely with a Gaussian distribution with a dispersion of 125 km s^{-1}. Elimination of the effect of foreground nebulae yields a true dispersion of 134 km s^{-1} for the nebulae in the central region. Because the planetary nebulae within 5° of the center show no pronounced flattening in their distribution and do not show any rotation around the center, I have assumed that the distribution of their random motions is isotropic and Maxwellian.

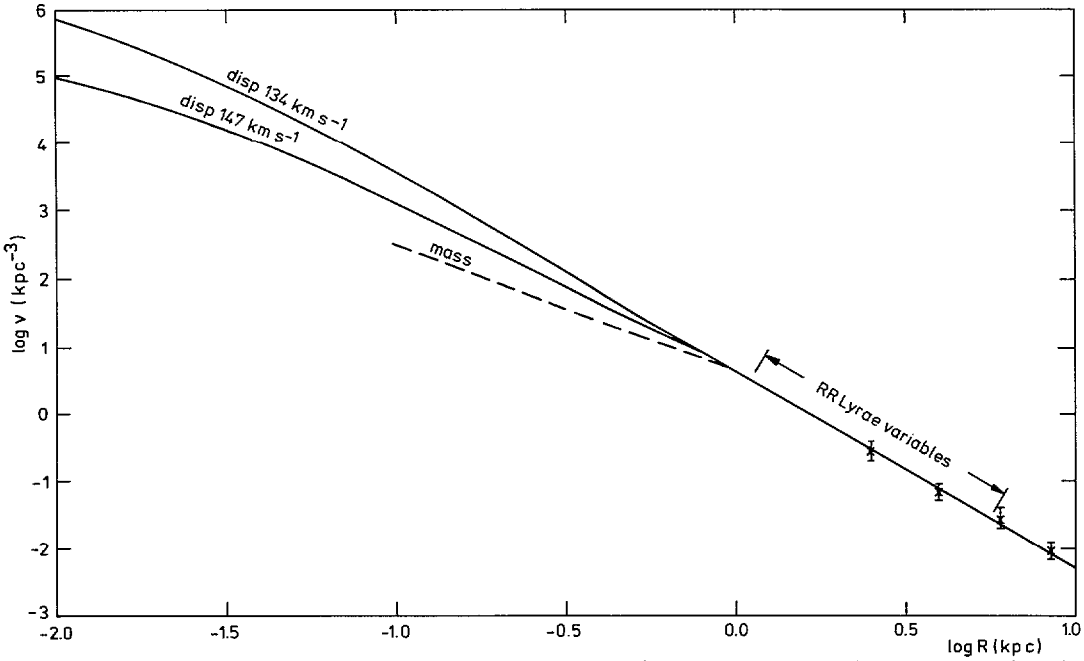

FIG. 1.—Space density of globular clusters (*crosses*; *vertical lines*, mean errors) as a function of the distance R from the galactic center, and its extrapolation to small R.

With proper units the density distribution is then given by

$$\frac{\nu(R)}{\nu(0)} = \exp - \frac{\Phi(R) - \Phi(o)}{\langle v_x^2 \rangle}\,, \tag{1}$$

where $(\langle v_x^2 \rangle)^{1/2}$ is the velocity dispersion in one coordinate and Φ is the gravitational potential.

With the aid of these data we can obtain an estimate of $\nu(R)$ for planetary nebulae down to small values of R. For the range between 0.08 and 1.0 kpc, ν is found to vary as $R^{-2.9}$ (see the upper curve in Fig. 1). We shall base the subsequent calculations on the supposition that the same distribution would apply to the RR Lyrae variables (and indeed the slope of -2.9 happens to fit precisely that observed for these variables between 1 and 5 kpc), and that this has also been the *initial* distribution of the globular clusters.

It should be noted that the density gradient derived is considerably steeper than that of the mass density found from the rotation and the infrared radiation, which is roughly indicated by the dashed curve. The difference appears to be larger than what can be attributed to the uncertainty in the velocity dispersion of the planetaries. This has a mean error of ± 13 km s^{-1}. The true dispersion may thus well be as high as 147 km s^{-1} but is unlikely to be much higher. The curve corresponding to a dispersion of 147 km s^{-1} has also been drawn in Figure 1. Even this is considerably steeper than the curve for the mass density. These data may indicate that the bulk of the mass is provided by a population with still higher velocities than the objects considered above, or, alternatively, that the gravitational field has been overestimated.

An alternative approach, used among others by Tremaine, Ostriker, and Spitzer (1975), is to make the *a priori* assumption that the distribution of mass is the same as that of the objects considered (i.e., the clusters). This "isothermal sphere" yields the much flatter distribution indicated by the dashed curve.

In the present *Letter* I use the somewhat more observational approach described above.

In summary, the distribution of the globular clusters in the inner part of the Galaxy has been estimated by a comparison of three classes of objects which dynamically appear to belong to the same general type of population, at least in the central region. The resulting densities are shown in Figure 1. It should be stressed that they may be uncertain by a factor of about 2 for the region between 1 and 3 kpc. For smaller R the uncertainty increases gradually, as illustrated by the divergence between the curves marked "disp 134" and "disp 147," respectively; the computations in the following have been made for each of the two extrapolations, in order to indicate the effect on the final results. In addition, we have to take account of the fact that the clusters in this inner region are probably radically depleted by the effects of dynamical friction, which will be discussed in § II. The actual distribution of the clusters may therefore deviate widely from the curves in Figure 1. These curves are nevertheless of interest because they give an indication of the *initial* cluster distribution and can therefore be used to obtain an estimate of the number that must have been drawn into the nucleus by dynamical friction, and thus provide information on the mass of the core formed in this way. The initial numbers of clusters within shells of various radii are shown under N_0 in Table 1. Because the dynamical friction depends on the mass, the clusters have been separated into two groups, with visual absolute magnitudes brighter and fainter than −9.5, respectively.

II. DYNAMICAL FRICTION AND MASS OF THE GALACTIC NUCLEUS

In a fascinating investigation Tremaine, Ostriker, and Spitzer (1975) have shown that, in the central regions of galaxies, globular clusters will be appreciably decelerated by stellar encounters and will ultimately be drawn into a small nucleus. In particular, they showed that the dense nucleus of about $5 \times 10^7 M_\odot$ observed in M31 may have been formed in this manner by the coalescence of some 25 clusters, mainly from the region within 2 kpc from the center. The average initial distance from the center of these clusters was 0.8 kpc and their average mass was $1.0 \times 10^6 M_\odot$.

In a later paper Tremaine (1976) has given results of similar calculations for our Galaxy. He has kindly furnished me with some unpublished numerical data. I infer from these that, of the clusters with a visual absolute magnitude brighter than −9.5 lying initially within R = 1730 pc, only 34% would remain after 10^{10} years, while those fainter than $M_V = -9.5$ would be reduced to 65%. In view of the data given for M31, the numbers drawn in from distances in excess of 1730 pc may probably be neglected. Unfortunately no calculations were available concerning the distribution of the captured clusters over the various radii within 1730 pc. I have tried to obtain a rough estimate of this by assuming that within each of the two mass groups all clusters with energies per unit mass less than a cutoff value E_m would be captured in the core or disappear by tidal disruption, while the clusters with higher energies would be unaffected. It is clear that this method can give only a rough approximation.

For computing E_m it was assumed that the velocity distribution was Maxwellian, with a dispersion of 134 or 147 km s^{-1} in one coordinate, and that the gravitational potential can, in the region concerned, be sufficiently represented by the formula given in the preceding section. Assuming a certain value of E_m, we can then in each distance shell find the fraction of clusters with E less than E_m, and therefore the fraction that should have disappeared in 10^{10} years. Adding the shells within R = 1730 should yield the fractions found by Tremaine for this region. Suitable values of E_m were found by trial and error.

Table 1 shows the effects of the dynamical friction computed in this way for the various distance shells in which it is appreciable. It may be seen that the numbers of clusters remaining within 100 pc from the center are negligible. Beyond 1000 pc the effects are small.

It is of interest to know the total mass drawn into the core by the dynamical friction. From the last line in Table 1 we see that, in the case with disp v_x = 134, 32 clusters from the bright group and 64 from the faint group have disappeared. These have not, however, all gone into the core, as a number will disintegrate by tidal action before they reach it. Tremaine (1976) estimates that the numbers surviving the tidal forces will be a factor 2 to 3 times less, say, 13 and 25 for the two brightness groups. If disp v_x is taken to be 147 instead of 134, the numbers will be reduced to about 7 and 15, respectively.

For estimating the mass we must determine the average effective mass of the clusters in each group. This was done with the aid of the luminosity distribution of the 94 clusters in Harris's Table 2 (Harris 1976) for which data on the integrated magnitude were available, mostly from Kron and Mayall (1960); for 17 clusters in the list such data were lacking. The distribution of the absolute magnitudes corrected for extinction is shown in Figure 2; the vertical lines above and under the plotted points indicate the statistical mean errors. The curve bears much resemblance to that found by van den Bergh (1969) for the globulars in M31, which was reproduced by Tremaine *et al.* From Figure 2 we find that 21% of all clusters have $M_V <$ −9.5.

Assuming a mass-luminosity ratio $M/L_V = 2.0$, and a cutoff at $M_V = -11.2$ in order to avoid divergence (see Tremaine *et al.*), I get a mean mass of $1.8 \times 10^6 M_\odot$ for the bright groups, and $0.7 \times 10^6 M_\odot$ for the faint group. Because the dynamical friction is proportional to $M^{3/2}$, the means were computed by averaging $M^{3/2}$ instead of M.

TABLE 1

NUMBERS OF CLUSTERS IN SHELLS OF THICKNESS 0.2 IN LOG R

R (pc)	disp v_x = 134 km s^{-1}				disp v_x = 147 km s^{-1}			
	$M_V \leq -9.5$		$M_V > -9.5$		$M_V \leq -9.5$		$M_V > -9.5$	
	N_0	N_{10}	N_0	N_{10}	N_0	N_{10}	N_0	N_{10}
1000..........	6.1	6.1	23.1	23.1	5.9	3.5	22.0	22.0
631...........	5.8	4.8	22.0	22.0	4.6	1.2	17.4	17.4
398...........	5.5	1.7	21.0	21.0	3.5	0.3	13.2	7.5
251...........	5.4	0.6	20.0	20.0	2.6	0.1	10.2	2.5
158...........	5.1	0.1	19.3	15.1	2.0	0	7.5	0.7
100...........	4.9	0	18.3	5.1	1.5	0	5.8	0.3
<80..........	12.9	0	48.3	1.7	3.0	0	11.5	0
<1260........	45.7	13.3	172.0	108.0	23.1	5.1	87.6	50.4

NOTE.—N_0, initial number; N_{10}, number left after 10^{10} years dynamical friction.

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TABLE 2

NUMBERS OF CLUSTERS IN RINGS OF RADIUS λ

λ (degrees)	disp v_x = 134 km s^{-1}				disp v_x = 147 km s^{-1}				
	$M_V \leq -9.5$		$M_V > -9.5$		$M_V \leq -9.5$		$M_V > -9.5$		
	N_0	N_{10}	N_0	N_{10}	N_0	N_{10}	N_0	N_{10}	Obs.
0.0–1.0......	10.0	0.6	37.8	22.0	4.3	0.2	16.0	2.6	0
1.0–2.0......	7.9	1.6	29.8	28.1	4.3	0.4	16.0	6.6	0
2.0–3.0......	5.2	2.3	19.5	18.6	3.7	0.8	13.7	9.3	1
3.0–4.0......	3.3	2.5	12.6	12.9	3.0	1.0	11.5	10.0	0
4.0–5.0......	2.7	2.3	10.3	10.0	2.4	1.3	9.2	9.2	2
<5.0........	29.1	9.3	110.0	91.6	17.7	3.7	66.4	37.7	3

NOTE.—N_0, initial number; N_{10}, number left after 10^{10} years dynamical friction.

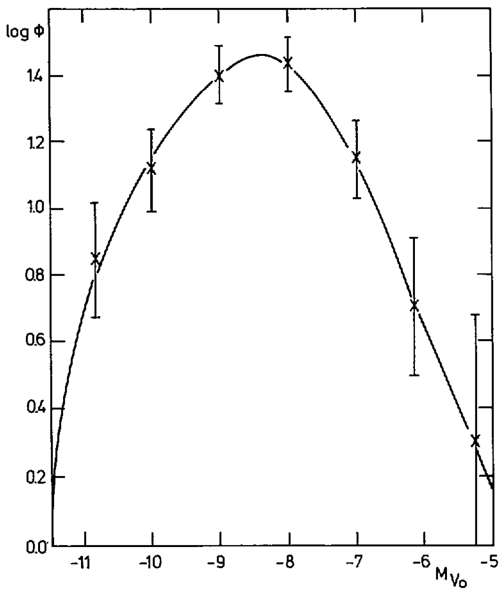

FIG. 2.—Absolute magnitude distribution of galactic globular clusters.

With these values the total mass of the core becomes roughly $4 \times 10^7 M_\odot$ for the case disp $v_x = 134$, and $2 \times 10^7 M_\odot$ for the case disp $v_x = 147$. Somewhat more direct estimates of the nuclear mass have been derived from the distribution of near-infrared radiation and from the velocity distribution of Ne II clouds, which gave between 2 and 6 times $10^6 M_\odot$ within $R = 0.5$ pc (see survey, Oort 1977). The difference with the above results should not be judged to be too disturbing, in view of the great uncertainties in both determinations, including that of the radius of the core produced by the clusters.

III. SURFACE DISTRIBUTION

From the space densities computed in § II and extended to larger values of R from the data given by Harris, we derived the numbers of clusters in various rings around the center. They are given in Table 2. The last column shows the known clusters.

At distances larger than 5° the tidal friction effects are negligible. The total number between 5° and 10° is computed to be 41; between 10° and 20° it is 36.

Table 2 indicates that even in the case of least concentration (corresponding to disp v_x 147 km s^{-1}) there should be 20 clusters within 3° of the center, whereas only one has been observed. (*Without* dynamical friction the expected number would be 58.) Practically all clusters in this region thus appear to be hidden by extinction. Of the hidden ones only one or two would belong to the intrinsically bright group.

It would evidently be of interest to find the actual number by a deeper search in the infrared.

In M31, where the absorption near the center is radically less, the depletion of clusters owing to the dynamical friction should be directly observable. A rough comparison is given in Table 3.

The data for the cluster distribution were taken from a compilation by Kinman (1962). In order to reduce a contamination with nonglobular clusters I have excluded those with $B - V < +0.5$. Absorption effects were minimized by counting only objects in the half southeast of the major axis, multiplying these by 2, and restricting the counts to objects brighter than $V = 17.5$. The median M_B is about -7.5, and is comparable with that of the clusters in the Galaxy. Although the distribution of the known clusters is evidently flattened, in particular farther than 15′ from

TABLE 3

NUMBERS OF GLOBULAR CLUSTERS IN THE GALAXY AND M31 AS A FUNCTION OF DISTANCE FROM THE CENTER

GALAXY		M31	
λ (degree)	n	λ (minutes)	n
<1	3 (20)	<0.9	0
1–2	7 (20)	0.9–1.7	2
2–3	10 (17)	1.7–2.6	2
3–5	22 (26)	2.6–4.4	6
5–10	41	4.4–8.7	30

the center, the clusters were counted in circular rings. With an assumed distance of 690 kpc, 0.'87 in M31 corresponds to 1° near the galactic center. The numbers for the Galaxy were taken from Table 2 for the case disp v_x 147 km s^{-1}; the initial numbers, before dynamical friction had set in, are in parentheses. The counts in M31 are at comparable linear distances from the center. Even when due account is taken of incompleteness, a comparison with the numbers in parentheses shows convincingly the depletion inside 1 kpc.

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REFERENCES

Arp, H. C. 1965, in *Galactic Structure*, ed. A. Blaauw and M. Schmidt (Chicago: University of Chicago Press), p. 401.
Harris, W. E. 1976, *A.J.*, **81**, 1095.
Kinman, T. D. 1962, *Ap. J.*, **137**, 213.
Kron, G. E., and Mayall, N. U. 1960, *A.J.*, **65**, 581.
Oort, J. H. 1977, *Ann. Rev. Astr. Ap.*, **15**, 295.
Oort, J. H., and Plaut, L. 1975, *Astr. Ap.*, **41**, 71.
Tremaine, S. D. 1976, *Ap. J.*, **203**, 345.
Tremaine, S. D., Ostriker, J. P., and Spitzer, L. 1975, *Ap. J.*, **196**, 407.
van den Bergh, S. 1969, *Ap.J. Suppl.*, **19**, 145.

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