GALACTIC ORBITS OF GLOBULAR CLUSTERS

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ГАЛАКТИЧЕСКИЕ ОРБИТЫ ШАРОВЫХ СКОПЛЕНИЙ

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To explain the nature of globular clusters, we must take into account their galactic orbits. Direct computation of most cluster orbits seems to be impossible because of the extremely low accuracy of their proper motions. Some indirect methods have been developed to determine the shapes and sizes of the orbits. S. von Hoerner (1955) found many galactic globulars with highly eccentric orbits by analysing their velocities and galactic positions. King (1962) suspected the galactic tidal field of being responsible for the limitation of the cluster radius. He derived a simple formula relating the perigalactic distance of a cluster R_p, the tidal radius R_t, the cluster mass M and the galactic mass M_G, contained in a sphere of radius R_p:

$$R_p = R_t \left[M_G(3 + e)/M\right]^{1/3} \tag{1}$$

This formula was used by Peterson (1974) to compute the eccentricities of 41 orbits in the Schmidt model of the Galaxy. For the Newtonian potential ($\phi \sim R^{-1}$) we obtained a more adequate relation,

$$R_p = R_t \left[\frac{M_G}{M} \frac{3 + 2e}{1 + e}\right]^{1/3}$$

and for an isothermal Galaxy we obtained

$$R_p = R_t \left[\frac{M_G}{M} (1 + \nu)\right]^{1/3} ,$$

where $\nu = 2e/\left\{(1 + e)^2 \ln\left[(1 + e)/(1 - e)\right]\right\}$. The eccentricity e can be defined as

$$e = (R_a - R_p)/(R_a + R_p),$$

R_a being the apogalactic distance of the cluster. Only the minimum value of e can be calculated because the actual apogalactic distance may be greater than the observed. We thus determined R_p and $e_{min} = (R - R_p)/(R + R_p)$ for 108 galactic globular clusters. The values of the angular tidal radii and the distance moduli of the globulars were taken from the lists of homogeneous data published by Kukarkin and Kireeva (1979) and by Kukarkin (1974). As the mass-to-light ratio we adopted the value $M/L_V = 2$ for all clusters, and as the galactocentric distance of the Sun the value $R_\odot = 8.5$ kpc. An isothermal model was assumed for the Galaxy mass distribution with the mass contained in the perigalactic sphere $M_G(R_p) = \alpha \times 10^{11} M$ $(R_p/15 \text{ kpc})$. The rotation curve in this composite model with $\alpha = 1$ for $R_p \leqslant 3.5$ kpc and $\alpha = 1.6$ for $R_p > 3.5$ kpc, fits the observed curve well. The influence of the mass cusp near $R_p = 3.5$ kpc can be neglected because of the weak dependence of the tidal radii on $M_G(R_p)$ and because of the small value of R_p for most globulars. Note that this method gives a limit for the perigalactic distance R_p which depends only weakly on the observed position of the cluster. We assumed the cluster radius to be conserved over a period of the order of 10^8 to 10^9 years.

The values of R_p, e_{min} and the mean square errors δ_e of e_{min} are given in the table. The distribution of perigalactic distances R_p and orbit eccentricities e_{min} are shown in Figs 1 and 2, respectively.

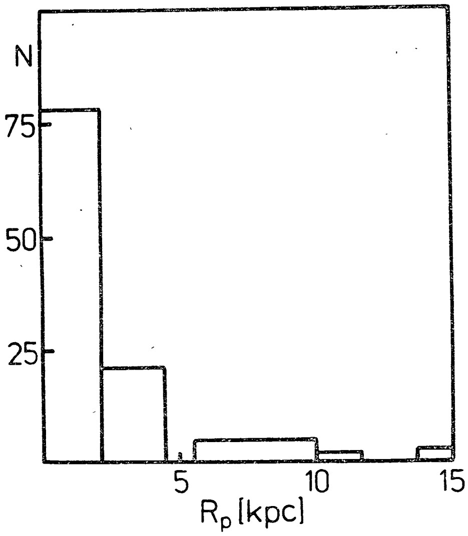

Figure 1.

In the case of 4 clusters only the lower limits of R_p were calculated because they are too extended. The mean-square errors δ_e were computed after Peterson (1974) and Kukarkin and Kireeva (1979). They reflect the intrinsic accuracy of computations rather than systematic effects caused by the differences in Galaxy models, galactocentric distance of the Sun, etc. If M/L_V changed from cluster to cluster, the mean-square error

δ_e would be greater by 0.02 to 0.05.

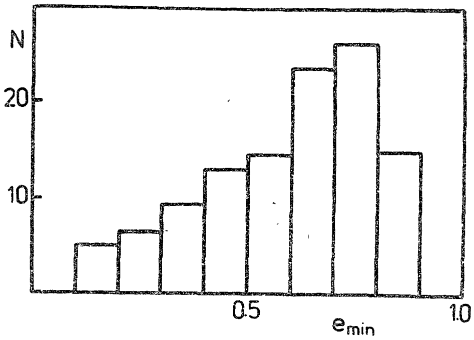

Figure 2.

TABLE.
Perigalactic distances and eccentricities.

NGC	R_p	e_{min}	δ_e	NGC	R_p	e_{min}	δ_e	NGC	R_p	e_{min}	δ_e
104	1.6	0.66	0.10	6139	1.4	0.41	0.09	6535	0.9	0.64	0.02
288	2.4	.65	.12	6144	2.0	.13	.13	6539	0.6	.78	.05
362	1.0	.80	.02	6171	1.9	.37	.10	6541	1.4	.41	.04
1261	1.2	.65	.01	6205	1.4	.72	.04	6544	0.4	.83	.04
Pal 2	2.4	.68	.04	6218	1.2	.58	.06	6553	0.4	.83	.05
1851	1.3	.84	.03	6229	1.6	.87	.01	6558	1.0	.30:	.28
1904	2.3	.79	.04	6235	1.5	.54	.14	6569	0.5	.55:	.19
2298	1.4	.84	.04	6254	0.9	.68	.04	6584	1.6	.56	.06
2419	9.9	.79	.03	6266	0.8	.46	.06	6624	0.7	.62	.11
2808	0.8	.87	.01	6273	1.0	.44	.09	6626	0.7	.62	.06
Pal 3	18.0	.61	.16	6284	1.7	.37	.11	6637	0.8	.54	.03
3201	2.4	.56	.03	6287	1.2	.22	.05	6638	1.0	.66	.08
Pal 4	11.0	.72	.09	6293	>1.6	-	-	6642	1.2	.37:	.23
4147	2.8	.76	.05	6304	1.0	.40	.11	6652	1.5	.72	.06
4372	2.2	.55:	.20	6316	>1.8	-	-	6656	0.6	.83	.01
4590	2.4	.62	.10	6325	>1.4	-	-	Pal 8	1.9	.61	.08:
4833	1.1	.72	.02	6333	1.1	.27	.09	6681	1.8	.49	.10
5024	2.2	.77	.03	6341	1.4	.74	.01	6712	0.7	.71	.07
5053	8.4	.26	.12	6342	2.0	.75	.04	6715	1.2	.68	.04
5139	1.5	.63	.12	6352	0.7	.76	.01	6723	1.7	.21	.10
5272	1.4	.77	.06	6355	0.7	.45:	.22	6749	1.2	.63	.04
5286	1.0	.75	.02	6356	1.3	.52	.03	6752	1.7	.54	.05
5466	7.2	.35	.08	6362	1.3	.61	.06	6760	0.6	.82	.01
5634	2.3	.74	.04	6366	1.5	.56	.06	6779	1.4	.72	.02
5694	2.6	.83	.05	6388	0.8	.74	.03	6809	1.5	.52	.04
IC4499	7.4	.17:	.24	6397	1.3	.68	.03	6838	0.9	.79	.02
5824	2.3	.74	.04	6401	0.8	.33:	.23	6864	1.9	.75	.04
Pal 5	>8.2	-	-	6402	0.9	.65	.04	6934	1.2	.80	.01
5897	2.5	.41	.05	6426	3.4	.48	.09	6981	2.3	.66	.02
5904	1.3	.64	.03	6440	0.4	.76	.10	7006	3.2	.80	.04
5927	1.0	.66	.03	6441	0.8	.17	.15	7078	1.7	.72	.02
5946	1.0	.64	.08	6453	0.5	.86	.18:	7089	1.5	.75	.03
5986	1.2	.51	.09	6496	0.8	.71	.08	7099	1.7	.61	.06
6093	1.7	.35	.06	6517	1.2	.60	.03	Pal 12	3.8	.63	.07
6101	2.0	.51	.15	6522	0.5	.69	.08	Pal 13	6.9	.52	.07
6121	0.8	.79	.03	6528	0.3	.79	.04	7492	10.4	.23	.03

Our perigalactic distances are systematically smaller than those of Peterson. This can partly be explained by the different Galaxy model, by the more accurate expression for R_p used in our paper and also by the systematic differences in the tidal radius data. The perigalactic distances of nearly 80 globulars are less than 2 kpc and of 35 globulars less than 1 kpc. Extremely low values of $R_p \lesssim 0.6$ kpc were found for clusters NGC 6440, 6522, 6528, 6544, 6656 and 6760 (all are very compact and have galactocentric radii R ranging from 9 to 16 kpc). The orbits of these clusters would be highly eccentric even in a more concentrated model of mass distribution in the Galaxy, $e_{min} \gtrsim 0.70$.

The correlation between e_{min} and R for all globulars is shown in Fig. 3. The eccentricities increase with distance from the centre. This trend is consistent with the idea of cluster formation in the early Galaxy with a low angular momentum. Some clusters, i.e. NGC 5053, 5466, 7492, IC 4499, Pal 3, 4, 5, do not satisfy this correlation. They have low eccentricities and large galactocentric distances. All these clusters have a low brightness and, consequently, their parameters are known with low accuracy. For example, their mass-to-light ratio may be much higher than 2 because the number of bright members in the cluster can be greatly influenced by poor star statistics. Some of these clusters are located in the plane of the Magellanic stream and, therefore, they may be of extragalactic nature. The assumption of the conservation of cluster radius is certainly more correct in the case of more massive clusters with long mean relaxation times (Surdin, 1978). Indeed, the correlation in the e_{min}-lg R plane is much more pronounced for massive globulars than for poor globulars. The question of possible cluster expansion has not been resolved yet. If cluster expansion were considered, the perigalactic distances of the clusters would decrease.

The solid line in Fig. 3 marks the lower boundary of the eccentricity distribution for massive clusters. It enables us to draw some conclusions about the peculiar velocities of protoclusters in the early Galaxy. The qualitative analysis of this line yields the simple law $V_{pec}(R) \sim R$ for the changes of the upper limit of the peculiar velocity.

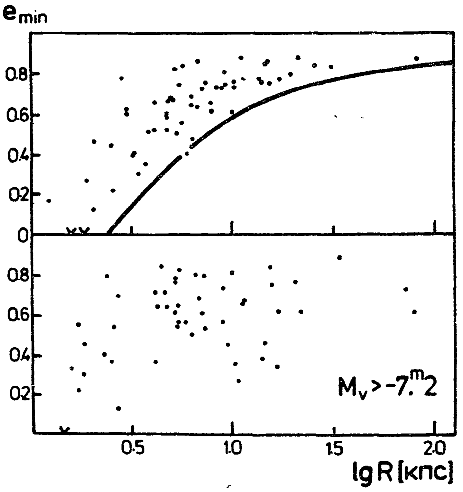

Figure 3.

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