Astronomical and Astrophysical Transactions (*AApTr*), 2025, Vol. 35, Issue 2, pp. 225–228,
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Determining the radial brightness gradient of globular clusters

D.A. Rashidov*, S.J. Turaev

National University of Uzbekistan named after Mirzo Ulugbek, 100174, Tashkent, Uzbekistan

Received 27 April, 2025; accepted 31 May, 2025

In this work, using the well-known chi-square minimization method – which minimizes the squared difference between observed and theoretical brightness – we have determined the corresponding structural parameters for globular clusters (GCs). As our observational data, we used surface brightness profiles constructed from Hubble Space Telescope (HST) observations. One of the structural parameters in our model characterizes the radial brightness gradient, and the associated uncertainties have been calculated.

Keywords: Globular clusters, surface brightness profile, structural parameters, radial brightness gradient

1 Introduction

Globular clusters in our Galaxy formed 11.7–12.7 billion years ago, making them among the oldest objects in the Universe (Belokurov and Kravtsov (2024); Nuritdinov et al. (2005)). Globular clusters are nearly spherically symmetric structures (Sil'chenko (2010)) whose brightness increases toward the cluster center. To date, approximately 170 globular clusters have been identified in our Galaxy, with masses reaching approximately $\sim 10^5$–$10^6\, M_\odot$ (Baumgardt and Hilker (2018); Balbinot and Gieles (2018); Borkova and Marsakov (2000)).

Observational data on the surface brightness of GCs date back to the 1960s (Kron and Mayall (1960)). Notably, the work by Trager et al. (1995) represents the most comprehensive compilation of surface brightness profile data. In that study, the authors obtained images of 125 GCs in our Galaxy using CCDs (charge-coupled devices) mounted on ground-based telescopes, and constructed the clusters' surface brightness profiles.

The aforementioned observational data were obtained using ground-based telescopes. For most clusters, the central surface brightness was found to be approximately 0.5 magnitudes brighter compared to previous ground-based measurements,

*Email: d.a.rashidov@gmail.com

with the maximum difference reaching about 2 magnitudes (Noyola and Gebhardt (2006)). Consequently, observations should be conducted using space telescopes to eliminate atmospheric effects and ensure a more accurate determination of both the stellar populations in clusters and their surface brightness.

Noyola and Gebhardt (2006) studied the central regions of clusters and constructed surface brightness profiles using images of the central areas of 38 clusters in our Galaxy, obtained with the WFPC2 (Wide Field Planetary Camera 2) from the HST archive. The authors modeled the surface brightness profiles by applying various power-law laws and presented the logarithmic slopes and their uncertainties to assess the central surface brightness of each cluster.

In this work, we present the structural parameters of clusters, including the radial brightness gradients for 38 GCs in our Galaxy, observed using the Hubble Space Telescope.

2 Radial brightness gradient

In the work by Nuritdinov et al. (2022), a generalized model for the surface density distribution in GCs was proposed in the following form:

$$\sigma(r) = \sigma_0 \left[1 + \left(\frac{r}{r_0}\right)^2\right]^{-\gamma}. \tag{1}$$

The parameter γ characterizes the degree of star concentration toward the cluster center, r_0 denotes the characteristic radius of the cluster's core region, and σ_0 represents the observed central surface density of the cluster.

In this work, the authors calculated the degree of star concentration toward the center for 26 globular clusters observed with the HST in our Galaxy. Additionally, Turaev et al. (2024) determined the values of the concentration parameter based on the surface density data of GCs in our Galaxy obtained as part of the Gaia DR2 program (Turaev et al. (2024)).

It is known that as the number of stars increases toward the center, their brightness also increases. Based on these considerations and by analogy with (1), one can propose the following surface brightness distribution expressed in units of mag/arcsec^2:

$$\mu_V(r) = \mu_{V0} \left[1 + \left(\frac{r}{r_0}\right)^2\right]^{\beta}. \tag{2}$$

It is evident that the exponent β, which also characterizes the radial brightness gradient (meaning the tempo of radial brightness increase), is positive. The central surface brightness μ_{V0}, the characteristic core radius r_0, and the parameter β are the structural parameters of GCs that are subject to evaluation.

In this work, the structural parameters of 38 GCs in our Galaxy were calculated and presented based on model (2).

Table 1 Structural parameters of GCs.

GC name	μ_{V0} (mag/arcsec^2)	$\Delta\mu_{V0}$ (mag/arcsec^2)	r_0 (arcsec)	Δr_0 (arcsec)	β	$\Delta\beta$
NGC 104	14.34	0.03	18.87	0.72	0.062	0.001
NGC 1851	13.57	0.04	2.51	0.09	0.058	0.001
NGC 1904	15.77	0.03	6.41	0.23	0.055	0.001
NGC 2298	18.65	0.04	12.86	0.53	0.047	0.001
NGC 2808	15.06	0.01	18.21	0.18	0.078	0.001
NGC 5272	15.86	0.03	15.76	0.58	0.054	0.001
NGC 5286	15.59	0.03	10.07	0.34	0.058	0.001
NGC 5694	15.72	0.08	2.19	0.14	0.056	0.001
NGC 5824	14.44	0.13	1.97	0.22	0.058	0.001
NGC 5904	16.06	0.04	20.59	1.07	0.062	0.001
NGC 6093	14.79	0.03	5.21	0.11	0.058	0.001
NGC 6205	16.62	0.04	42.76	3.50	0.055	0.004
NGC 6254	17.62	0.02	20.31	1.15	0.047	0.001
NGC 6266	14.98	0.07	8.10	0.61	0.078	0.001
NGC 6284	14.74	0.14	0.83	0.13	0.054	0.001
NGC 6287	18.48	0.04	12.43	1.26	0.058	0.002
NGC 6293	14.83	0.35	1.70	0.53	0.056	0.002
NGC 6333	17.08	0.07	19.99	1.85	0.058	0.003
NGC 6341	15.30	0.02	9.64	0.25	0.052	0.001
NGC 6352	18.33	0.03	22.93	1.90	0.047	0.003
NGC 6388	14.81	0.06	4.79	0.32	0.054	0.001
NGC 6397	15.35	0.15	2.04	0.46	0.028	0.001
NGC 6441	14.89	0.04	6.50	0.25	0.061	0.001
NGC 6528	16.52	0.08	3.24	0.27	0.045	0.001
NGC 6535	18.79	1.48	1.95	1.80	0.027	0.004
NGC 6541	14.84	0.05	4.89	0.29	0.052	0.001
NGC 6624	14.65	0.04	2.55	0.11	0.051	0.001
NGC 6626	15.57	0.02	9.50	0.30	0.053	0.001
NGC 6637	16.33	0.04	10.88	0.52	0.043	0.001
NGC 6652	13.94	0.19	1.01	0.16	0.052	0.001
NGC 6681	13.66	0.10	0.84	0.09	0.046	0.001
NGC 6712	18.55	0.03	20.56	1.72	0.029	0.001
NGC 6715	14.31	0.03	4.10	0.09	0.062	0.001
NGC 6752	14.58	0.09	4.28	0.59	0.041	0.002
NGC 7078	12.85	0.19	1.72	0.38	0.053	0.002
NGC 7089	15.20	0.03	13.18	0.40	0.065	0.001
NGC 7099	14.24	0.15	1.11	0.18	0.040	0.001

3 Calculation of structural parameters

To compute the three structural parameters in model (2), which is used to describe the surface brightness of GCs, it is necessary to minimize function

$$F\left(r_i, \mu_{V0}, r_0, \beta\right) = \sum_{i=1}^{n} \left[\mu_{V_i}(obs) - \mu_V(r_i, \mu_{V0}, r_0, \beta)\right]^2, \tag{3}$$

which represents the sum of the squared differences between the theoretical brightness ($\mu_V(r_i, \mu_{V0}, r_0, \beta)$) and the observed brightness ($\mu_{V_i}(obs)$). To minimize function (3), it is sufficient to use the simplex method, which has long established itself in solving many astrophysical problems (Ashurov and Nuritdinov (2001)).

The values of the surface brightness distribution parameters specified in equation (2) for 38 GCs were determined using the standard χ^2 minimization method, employing the following function:

$$\chi^2 = \sum_{i=1}^{n} \frac{\left[\mu_{V_i}(obs) - \mu_V(r_i, \mu_{V0}, r_0, \beta)\right]^2}{\sigma^2_{\mu_V i}}. \tag{4}$$

The calculated values of the structural parameters and their uncertainties are presented in Table 1.

It is worth noting that the surface brightness profile of NGC 5897 is distinguished from those of other clusters by the presence of sharp, wave-like structures. For this reason, the structural parameters of this cluster could not be reliably determined. The β parameters found for all other globular clusters lie in the range from 0.027 to 0.078.

4 Conclusions

We computed the structural parameters for 38 globular clusters observed with the Hubble Space Telescope, which, unlike ground-based telescopes, provides sufficient accuracy. The structural parameters and their uncertainties were determined using the chi-square minimization method. It is noteworthy that the parameter β in the model is significant, as it allows for a classification of globular clusters analogous to that presented in Nuritdinov et al. (2022). This classification opens up opportunities for a more systematic study of the early stages of the Universe's formation.

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