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Dependencies of physical parameters of globular clusters on their age

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Nuritdinov et al. (2021) calculated the values of the concentration parameter, which represents the increasing concentration of stars towards the center of these clusters, using surface density observations of 26 Globular clusters (GCs) obtained with the Hubble Space Telescope (HST). This work investigates the empirical relationship between the age of GCs and the values of the concentration parameter. Since a number of studies have been conducted to date using different methods to determine the age of GCs, the results differ from each other. Therefore, we studied the connections between the values of the concentration parameter, taking the age values of the clusters for each study separately.

Keywords: Age, concentration parameter, correlation, globular clusters, structural parameters

1 Introduction

GCs are dense, spherical collections of stars that are among the oldest and most stable stellar systems in the Universe. They are typically composed of hundreds of thousands of stars, packed into regions with diameters of only a few hundred light-years. GCs represent some of the oldest structures in the Universe, and determining their ages is critical for constraining the overall age of the Universe itself. Accurately determining the age of GCs is a challenging but essential aspect of astrophysical research. The most commonly used methods for age determination are: Main Sequence Turnoff (MSTO) method (Wu, Ya-Qian et al. (2017)), White Dwarf Cooling Sequences method (García-Berro et al. (2011)), Isochrones and Stellar Population modeling (Li and Han (2008)), Gravitational microlensing, which offers an alternative technique to estimate the ages of stars within GCs, particularly in systems that are difficult to analyze directly due to their distance or obscured environments (Paczynski (2006)). Over time, the cluster's stellar population undergoes significant evolution, leading to changes in the cluster's

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structural and dynamical characteristics. Several key dynamical processes are closely linked to the cluster's age:

– As a GC ages, mass segregation occurs, where the more massive stars sink toward the center of the cluster, while lighter stars are pushed to the outer regions (Alexander and Hopman (2005)).

– In older GCs, the cumulative effect of dynamical relaxation and mass segregation leads to a phenomenon known as core collapse (Heggie (2003)).

– GCs, especially those near the galactic center, are subject to tidal forces from their host galaxies (Baumgardt and Makino (2003)).

– The age of a GC is also related to its relaxation timescale, which is the time it takes for the stars in the cluster to achieve a state of dynamic equilibrium (Merritt (2013)). Given that GCs undergo the above-mentioned significant dynamical and structural changes over time, we assume that the values of the concentration parameter, which represents the concentration of stars towards the cluster center, also change depending on the cluster age, and we examine the relationships between these parameters. We have concentration parameter values of 26 GCs from Nuritdinov et al. (2021). Since a number of studies have been conducted to date using different methods to determine the age of GCs, the results differ from each other. Therefore, we study the relationships between the values of the concentration parameter, taking the age values of the clusters for each study separately.

2 Concentration parameter of globular clusters

Nuritdinov et al. (2021) introduced the concept of the "concentration parameter" (γ) as a measure of the rate at which stellar concentration increases toward the center of GCs. This was achieved using the simplex method applied to observational data on the apparent surface density of 26 GCs observed by HST and modeled within the framework of the King model (King (1966)). The mathematical formulation is given by the equation:

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

where γ, r^*, and σ_0 are free parameters. Here, σ_0 represents the central concentration; γ, the concentration parameter; r^* denotes the distance from the horizontal baseline to the sharp deviation point of the observed surface density profile.

The free parameters were determined by minimizing the following observational function using the simplex method (Ashurov and Nuritdinov (2001); Turaev et al. (2024)):

$$F(r,\gamma,r^*\sigma_0) = \sum \left[\sigma(r,\gamma,r^*\sigma_0) - \sigma_{obs}^{(k)}\right]^2, \tag{2}$$

where $\sigma_{obs}^{(k)}$ is the observed apparent surface density measured from observational data over equal surface annuli. The ages of GCs, which are given separately for particular research studies, and concentration parameter values corresponding to the above method, are listed in Table 1, column 7.

Table 1 Age values and concentration parameter for 22 GCs.

GC name	Valcin	Dotter	Forbes	VandenBerg	Koleva	(γ)
AM 1	–	11.1	11.1	–	–	1.73
Eridianus	–	10.5	8.9	–	–	1.52
NGC 104	13.54	12.75	13.06	11.75	10.7	0.72
NGC 288	11.2	12.5	10.62	11.5	–	1.33
NGC 1851	12.27	–	9.98	11	9.2	1.97
NGC 1904	–	–	11.14	–	11.7	0.89
NGC 2419	–	13	12.3	–	–	1.17
NGC 5024	13.31	13.25	12.67	12.25	–	1
NGC 5272	12.6	12.5	11.52	11.75	–	0.8
NGC 5466	12.31	13	13.57	12.5	–	1.44
NGC 5824	–	–	12.8	–	–	0.73
NGC 5904	12.75	12.25	10.62	11.5	10.9	0.67
NGC 6121	13.01	12.5	12.54	11.5	–	0.79
NGC 6205	13.49	13	11.65	12	12	1.03
NGC 6266	–	–	11.78	–	12	0.86
NG 6341	13.3	13.25	13.18	12.75	–	1.02
NGC 6809	13.93	13.5	12.29	13	–	0.84
NGC 6864	–	–	9.98	–	–	1.17
NGC 7089	13.08	12.5	11.78	11.75	–	0.89
Pal3	–	11.3	9.7	–	–	2.13
Pal 4	–	10.9	9.5	–	–	2.1
Pal 14	–	12.5	10.5	–	–	0.99

3 Correlation between concentration parameter and age of GCs

We cite the following as the main studies that provide age values for GCs.

VandenBerg et al. (2013) provided age estimates for 55 GCs using photometric data from the HST's Advanced Camera for Surveys. Their approach involved fitting the observed distribution of stars at the zero-age horizontal branch's lower limit, yielding age uncertainties of ± 0.25 Gyr.

Similarly, Valcin et al. (2020) reported absolute age values for 68 Galactic GCs, derived from the analysis of stellar distributions. Their findings indicated that the average age of the oldest GCs is $t_{GC} = 13.32 \pm 0.1$ Gyr, with the associated uncertainty linked to methods that are largely independent of cosmological parameters. From these measurements, they estimated the Universe's age to be $t_U = 13.5 \pm 0.6$ Gyr.

Dotter et al. (2010) analyzed the mean color differences between horizontal branch (HB) stars and the red giant branch across 60 GCs located within approximately 20 kpc of the Galactic center, utilizing photometric observations from the HST's Advanced Camera for Surveys. Their analysis provided further insights into the age distribution and evolutionary properties of these clusters.

Further contributing to this discourse, Forbes and Bridges (2010) proposed that the Milky Way's structure was significantly formed through the accretion of smaller galactic systems and their associated GC populations. They analyzed a high-quality database comprising age and metallicity information for 93 Milky Way GCs using the color-metallicity relationship. Their findings suggest that the oldest clusters exhibit an

average age-metallicity ratio of approximately 12.8 Gyr, with the remaining clusters being comparatively younger.

Additionally, Koleva (2008) utilized spectral synthesis models to investigate observed optical spectra from GCs, focusing on aspects such as age, metallicity, and line broadening induced by intrinsic kinematic motions. Koleva employed STECKMAP a non-parametric regularization method, and NBURSTS, a parametric non-linear minimization approach. Their analysis compared three spectral synthesis models for single stellar populations, emphasizing the detailed spectroscopic constraints on GC ages and evolutionary properties.

These various approaches highlight the multi-faceted strategies employed to infer the ages of GCs, using both photometric and spectroscopic observations. Each methodology brings unique strengths and uncertainties, contributing to our understanding of the GC age distribution and its correlation with cluster properties.

We examine the empirical connections between the values of the concentration parameter and the ages of GCs found based on the HST observational data. In this case, we found good empirical correlations between the concentration parameter and the age values reported in Valcin et al. (2020) and Dotter et al. (2010) (–0.56 and –0.70, respectively). An empirical correlation was found with age values given in Forbes and Bridges (2010) (–0.59). Figure 1 presents diagrams of these empirical relationships found.

Below we present the empirical formulas for the relationships between age-related values of GC ages and concentration parameters γ.

Of the 68 GCs for which age values were given in Valcin et al. (2020), concentration parameter values were found for only 12, and the correlation coefficient between these parameters is $cc = –0.56$. The corresponding empirical formula is

$$\gamma = -0.283(\pm 0.13)\tau_{GC} + 4.70(\pm 1.72). \quad (3)$$

In Dotter et al. (2010), concentration parameter values were calculated for 18 of the 60 clusters for which age values were given, and the correlation coefficient between these parameters is $cc = –0.70$. The corresponding empirical formula:

$$\gamma = -0.36(\pm 0.09)\tau_{GC} + 5.66(\pm 1.17). \quad (4)$$

In Forbes and Bridges (2010), concentration parameter values were calculated for 22 of the 93 clusters for which age values were given, and the correlation coefficient between these parameters is $cc = –0.59$. Empirical formula:

$$\gamma = -0.20(\pm 0.06)\tau_{GC} + 3.48(\pm 0.72). \quad (5)$$

In VandenBerg et al. (2013), concentration parameter values were calculated for 12 of the 55 clusters for which age values were given. Unfortunately, in this case, the correlation coefficient is very small (–0.25). Age values are given for 40 clusters in Koleva (2008). Of these, the concentration parameter values were determined for only 6. Therefore, we did not present the results in this case.

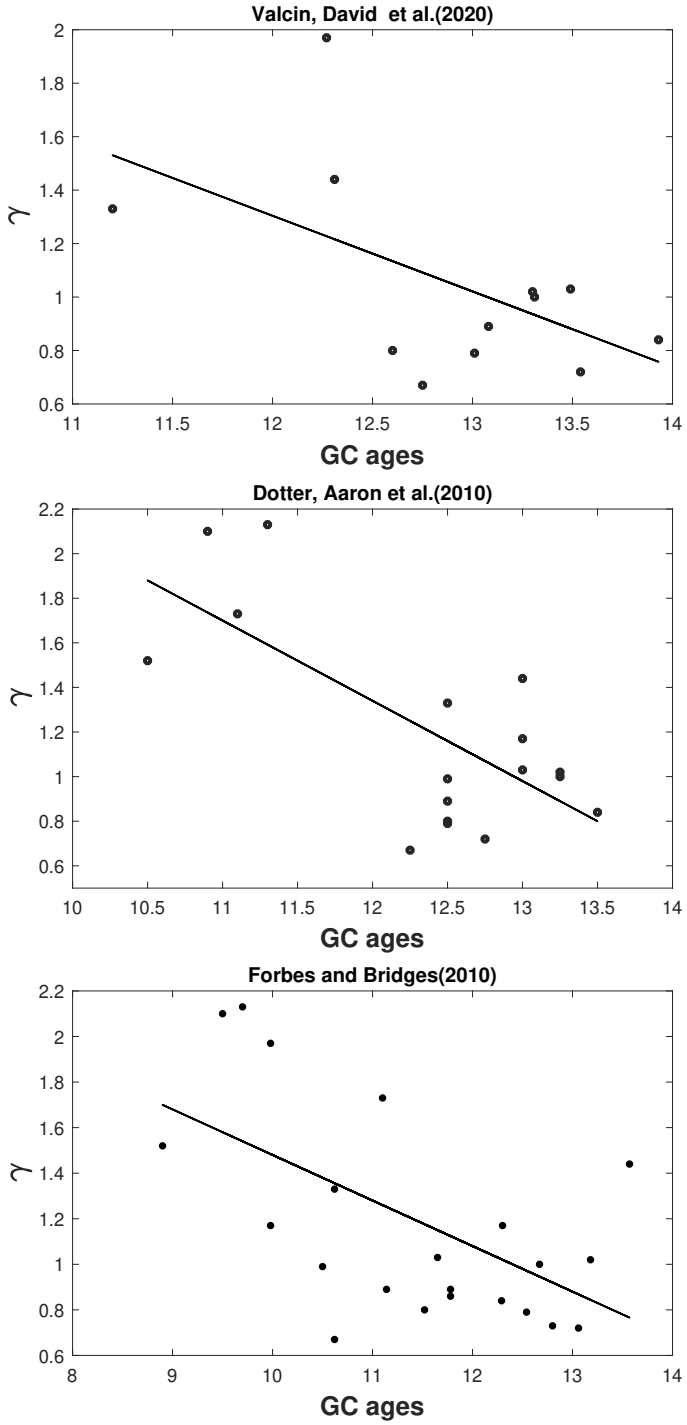


Figure 1 Diagrams of the dependence between the concentration parameter γ and GCs ages.

4 Conclusions

In this study, we investigated the empirical relationship between the ages of GCs and their concentration parameters (γ), which characterize the degree of stellar concentration toward the cluster center. Using surface density observations from the HST, we determined the concentration parameter values for 26 Galactic GCs. Since different studies use various methods to estimate GC ages, leading to discrepancies in age determinations, we analyzed the correlation between the concentration parameter and GC ages based on each study separately.

Our analysis revealed no significant empirical correlation between GC ages and concentration parameters when using age values derived from GAIA DR2 observational data, this could be due to the lower quality of these data compared to HST observations. However, a clear negative correlation was identified between concentration parameter values and GC ages derived from high-quality HST data.

This study presents, for the first time, empirical evidence for a measurable relationship between GC age and stellar concentration, offering a new perspective on the structural evolution of GCs and providing a potential indirect method for age estimation based on observed concentration parameters.

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