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RELATIONSHIP BETWEEN THE CONCENTRATION PARAMETER AND INTERMEDIATE-MASS BLACK HOLES IN GLOBULAR CLUSTERS

Annotatin

This article investigates the empirical relationship between the concentration parameter, which characterizes the rate of stellar density increase toward the centers of globular clusters (GCs), and the masses of central intermediate-mass black holes (IMBHs). In this study, only theoretically derived values of IMBH masses are considered. The concentration parameters were calculated based on the surface density profiles obtained from Gaia DR2 observations. The concentration parameter can be employed as a diagnostic tool for assessing the properties and formation processes of central IMBHs in GCs.

Keywords: central black holes, globular clusters, stellar concentration parameter, simulations, surface density of clusters

СВЯЗЬ МЕЖДУ ПАРАМЕТРОМ КОНЦЕНТРАЦИИ И ЧЕРНЫМИ ДЫРАМИ ПРОМЕЖУТОЧНОЙ МАССЫ В ШАРОВЫХ СКОПЛЕНИЯХ

Аннотация

В данной статье исследуется эмпирическая связь между параметром концентрации, который характеризует скорость увеличения плотности звёзд по направлению к центрам шаровых скоплений (ШС), и массами центральных чёрных дыр промежуточной массы (ЧДПМ). В этом исследовании рассматриваются только теоретически определённые значения масс ЧДПМ. Параметры концентрации были рассчитаны на основе профилей поверхностной плотности, полученных из наблюдений Gaia DR2. Параметр концентрации может использоваться в качестве диагностического инструмента для оценки свойств и процессов формирования центральных ЧДПМ в ШС.

Ключевые слова: центральные чёрные дыры, шаровые скопления, параметр концентрации звёзд, моделирование, поверхностная плотность скоплений.

KONSENTRATSIYA PARAMETRI VA SHARSIMON TO‘DALARDAGI ORALIQ MASSALI QORA O‘RALAR ORASIDAGI BOG‘LANISH

Annotatsiya

Ushbu maqolada sharsimon to‘dalar (ShT) markaziga tomon yulduzlar zichligining ortish tezligini xarakterlovchi kontsentratsiya parametri va markaziy oraliq massali qora o‘ralar (OMQO’) massalari o‘rtasidagi empirik bog‘liqlik o‘rganiladi. Tadqiqotda faqat nazariy usullar yordamida hisoblangan OMQO’ massalari ko‘rib chiqiladi. Kontsentratsiya parametr qiymatlari Gaia DR2 kuzatuvlari asosida olingan sirt zichligi profillari bo‘yicha hisoblab chiqilgan. Kontsentratsiya parametri markaziy OMQO’larning xususiyatlari va shakllanish jarayonlarini baholashda diagnostik vosita sifatida qo‘llanishi mumkin.

Kalit so‘zlar: markaziy qora o’ralar, sharsimon to’dalar, yulduzlarning kontsentratsiya parametri, modellashtirish, to‘dalarning sirt zichligi.

Introduction. In our previous study [1], we investigated the empirical dependencies between IMBH masses, determined from observational data in the centers of GCs, and the main physical parameters of clusters. As a logical continuation of that work, here we examine the empirical relations between the concentration parameter, calculated using the surface density profiles of GCs obtained from Gaia DR2, and theoretically estimated characteristics of IMBHs.

Currently, central IMBH masses have been observationally determined for only 16 Galactic clusters (see, e.g., [2 – 7]), while their values for most clusters are inferred mainly through theoretical models. In many studies, estimates of IMBH masses in GC centers have been presented, and correlations have been reported between the velocity dispersion of stars in galactic nuclei and the masses of central supermassive black holes [8].

$$M_{IMBH}=1.2\times10^{8}M_{\odot}\left({}^{\sigma_e}/_{200km/s}\right)^{3.75\pm0.3} \quad (1)$$

By analogy, it has been hypothesized that a similar dependence may exist between the central velocity dispersion of GCs and their central IMBH masses.

For example, Safonova (2010) [9] estimated IMBH masses in 30 GCs using central velocity dispersions. However, the obtained values differ substantially from those of other works. For instance, for NGC 2808, Safonova reported an IMBH mass of **1,874,700 M$_{\odot}$**, whereas Maccarone (2004) [10] obtained **550 M$_{\odot}$**. Similarly, for NGC 6093, Safonova estimated **2,610,000 M$_{\odot}$**, while Bash et al. (2008) [11] reported only **1600 M$_{\odot}$**. In some cases, IMBH mass estimates even exceed the total cluster mass, e.g., for NGC 6715, Safonova's IMBH mass is **10,491,000 M⊙**, while Baumgardt's catalog (2018) [12] lists the total cluster mass as only **1,410,000 M⊙**. Due to such inconsistencies, Safonova's estimates are not considered in this work.

Sedda et al. (2019) [13], within the MOCCA-SURVEY project (Milky Way Orbit-Centric Cluster Catalog), modeled stellar population dynamics in clusters, analyzing over 2000 models. They identified IMBHs in 51 out of 153 modeled GCs. Their results show IMBH masses significantly higher than observational estimates. In this paper, we test the empirical dependencies obtained in our previous work against theoretically derived IMBH masses.

Data and Model. Nuritdinov et al. (2021) [14] introduced the concentration parameter (γ) as a measure of the rate of stellar density increase toward GC centers. It was determined using a simplex method applied to the surface density profiles of 26 GCs observed with the Hubble Space Telescope (HST) and analyzed with King's model. The generalized model is:

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

Here, γ, r^* and σ_0 are free parameters, γ represents the degree of stellar concentration toward the cluster center, r^* is the core radius of the cluster, and σ_0 is the central surface density. The authors calculated these free parameters for 81 GCs given de Boer et al. (2019) [15]. The free parameters were determined by the method of squared function minimization (5).

Using Gaia DR2 apparent surface density data [16], we calculated the concentration parameters for GCs following this methodology. The Nuker model (3), which is used for surface density and surface brightness profiles of elliptically shaped celestial bodies, such as galaxies, GCs, is well suited for Gaia observations [17]:

$$I(r)=I_b 2^{(\beta-\gamma)/\alpha}(r/r_b)^{-\gamma}[1+(r/r_b)^{\alpha}]^{(\gamma-\beta)/\alpha}, \qquad (3)$$

We generalize model (3) as follows:

$$\sigma(\gamma_1,\gamma_2,r^*,\sigma_0)=\sigma_0 \left(\frac{r}{r^*}\right)^{-\gamma_1} \left[1+\left(\frac{r}{r^*}\right)\right]^{-\gamma_2} \qquad (4)$$

Here $\gamma_1 + \gamma_2 = \gamma$ - consentrstion parameter of the cluusters. γ_1 and γ_2 where the free parameters define inner and outer concentration slopes.

$$\chi^2 = \sum_n \frac{\left|\sigma_{obs}^{(n)} - \sigma(r^*,\sigma_0,r_0,\gamma)\right|^2}{\sigma(r_n,\sigma_0,r^*,\gamma)} \to \min. \qquad (5)$$

$\sigma_{obs}^{(n)}$ - is the observed surface density in equal annuli. The Nuker model allows one to compute both inner and outer concentration parameters, yielding higher precision compared to King's model. The values of the concentration parameters were calculated by us in accordance with the above-described methodology.

Empirical Relation and Discussion. Turaev et al. (2024) computed concentration parameters for GCs using Gaia DR2 surface density profiles, combined with IMBH mass estimates from Sedda et al. (2019) for 16 clusters. A weak correlation was found (cc = 0.38) between IMBH mass and concentration parameter. The empirical relation is:

$$\gamma=0.78(\pm0.42)\log(M_\bullet/M_\odot) - 1.64(\pm1.14) \qquad (6)$$

Table 1. Concentration parameters and IMBH masses for 16 GCs (Sedda et al. 2019).

GC name	**Log(M•/M⊙)**	**γ**
NGC 6397	3.99	2.19
NGC 6352	4.32	2.14
NGC 6681 (M70)	3.86	1.55
NGC 6366	4.44	5.44
NGC 6325	3.76	4.94
NGC 6121 (M4)	4.05	4.14
NGC 5272 (M3)	4.12	3.58
NGC 4147	4.28	3.53
NGC 2298	4.32	5.18
IC 1276	4.34	8.07
NGC 6093	3.56	3.87
NGC 6254 (M10)	3.92	4.14
NGC 1851	3.54	2.46
NGC 6171 (M107)	4.15	4.33
NGC 6235	4.37	3.89
NGC 6717	4.06	2.46

The obtained correlation coefficient (cc = 0.38) is significantly weaker compared to our earlier result (cc = 0.72) based on observational IMBH masses. Furthermore, no robust correlations were found between IMBH masses (Sedda et al. 2019) and other physical parameters of GCs. These discrepancies likely arise from uncertainties in theoretical models used to infer IMBH masses.

Our previous work demonstrated a strong correlation (cc ≈ 0.72) between IMBH masses and concentration parameters derived from observational data. In contrast, this study finds only a weak correlation (cc ≈ 0.38) using theoretically estimated IMBH masses. In many cases, IMBH mass estimates even exceed host cluster masses. Such discrepancies highlight the uncertainties inherent in theoretical dynamical models, which depend strongly on initial conditions, stellar population assumptions, and interaction mechanisms. These uncertainties reduce the reliability of IMBH mass estimates and weaken empirical correlations.

Nevertheless, the presence of even a weak correlation between concentration parameters and IMBH masses indicates that concentration may remain a useful diagnostic for probing central massive objects in GCs. Its sensitivity, however, depends on whether the IMBH masses are derived observationally or theoretically.

Conclusion. This study analyzed the empirical relationship between the stellar concentration parameter and the properties of central IMBHs and black hole subsystems in GCs. Using Gaia DR2 surface density data and the Nuker model, concentration parameters were determined, and correlations with theoretically estimated IMBH masses were examined.

The analysis showed that the stellar concentration parameter remains an informative indicator of the presence and properties of central massive black holes. Significant empirical dependencies were found between concentration and BH subsystems, particularly in terms of their total mass and population size. However, due to large uncertainties in theoretical IMBH mass estimates, interpretation of these correlations requires caution. Observational data, combined with improved dynamical models and machine learning techniques, will be essential for more reliable conclusions.

Thus, the concentration parameter should be regarded as a promising diagnostic tool for identifying central dark components in GCs, especially where direct observations remain challenging.

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