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ANALYSIS OF OBSERVATION DATA AND THE THEORY OF THE ORIGIN OF GLOBULAR CLUSTER SYSTEMS

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Abstract. The paper presents the results of a statistical analysis of a consolidated catalog of 441 globular cluster systems of various types of Hubble galaxies. The necessary relationships between the physical parameters of globular cluster systems and their galaxies were constructed in order to identify the main distinctive properties of various globular cluster systems. Empirical relationships have been found between the main physical parameters of globular cluster systems and their parent galaxies for the main morphological types of galaxies in the Hubble sequence. A possible theory for the origin of poor globular cluster systems is proposed. Nonstationary dispersion equations for high-degree modes are derived that are relevant to the origin of poor globular cluster systems. The issues of instabilities leading to the formation of poor systems of globular clusters in the case of bulk oscillation modes for a nonlinear model of a collapsing protogalaxy are studied. The critical values of the initial virial ratio are determined and the dependencies between the model parameters are constructed.

Keywords: globular clusters, globular cluster systems, catalog, empirical dependences, instability, virial parameter, increment

I. INTRODUCTION

Globular clusters (GC) are the most unique objects in the problem of comparing two scenarios for the origin of galaxies: cascade fragmentation and hierarchical clustering. In addition, according to modern observations, almost all types of Hubble tuning fork galaxies contain some, to varying degrees, globular clusters systems (GCS). The study of the GCS of galaxies began to be carried out more actively with the advent of CCD-cameras. For example, Zinn [1] investigated the spatial distributions, kinematics and metallicities of 121 Milky Way globular clusters and showed that the Milky Way globular cluster system consists of two distinct subpopulations. After that, Armandroff [2] studied the properties of the GCS of a thick disk and found the rotation speed of this system: 19329 km/sec. Battistini et al. [3] studied various properties of the M31 GCS. While studying the distribution of metallicity and the kinematics of the M31 globular cluster, they considered models of galaxy formation that use the age, distance, and brightness functions of the globular cluster. Subramaniam and Sagar [4], having studied the GCS in giant elliptical galaxies, found that at present the number of clusters in each of them is approximately several thousand. The distances to them are comparatively greater, so it is impossible to observe their individual members, but one can only observe and study them as a whole. Further, Vesperini [5] studied the evolution of the properties of the GCS (mass function, spatial distribution, number of clusters, specific frequency) in our Galaxy and in elliptical galaxies, and found the dependence of the evolution of the GCS on their initial mass function and on the properties of host galaxies. Kundu and Whitmore [6] studied the GCS of more than 50 galaxies. They found that, of these, almost half of the GCS of galaxies have a bimodal distribution of metallicity (or color), and that in each of these GCS, metal-rich globular clusters (or ”red” globular clusters) are concentrated closer to the center of the galaxy than metal-poor globular clusters (or ”blue” globular clusters).

Using the age of the GCS, one can imagine the early stage of galaxy formation [7-8]. Having determined the spatial distribution and distribution of colors of globular clusters located around galaxies, one can judge the scenarios for the formation of galaxies. In classical scenarios for the formation of spiral galaxies, the stellar population of the halo contains the oldest stars in the galaxies. The age and metallicity of the Galactic globular cluters make it possible to build a chronological order of the formation of the population of the Milky Way halo. Using these results and data from the Hubble Space Telescope, one can also

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explore the formation chronology of other spiral galaxies in the Local Group, such as M31 and M33. These data are the latest results related to earlier epochs of star formation both in the Milky Way, M31, M33, and in their GCS.

We note that there are GCS in which the distribution of color or metallicity is described by a single Gaussian distribution. For example, Chapelon et al. [8] carried out photometry of the GCS around NGC 7457 and found that there are no two globular cluster subsystems in the GCS of this galaxy.

Ashman and Zepf [9] noted that globular clusters can be formed by merging two massive gas clouds, which leads to the formation of elliptical galaxies with high metallicities, with a metallicity distribution having a multimodal maximum. Metallicity information for a large number of globular clusters in a galaxy can help limit models of galaxy formation. In [10], the GCS around 12 galaxies was studied and the velocities of individual clusters were measured. From the velocity data, the dynamic masses of the host galaxy are estimated by applying the virial theorem. After averaging and plotting the dynamical masses in several ways, in this work the mass curves for all observed galaxies are obtained. The calculated dynamic mass curve for each galaxy increases with the effective radius. In addition, red (metal-rich) and blue (metal-poor) globular clusters were separated when assessing the dynamic mass. The author has found statistical relationships between the dynamic masses of galaxies and the masses of the clusters themselves and the masses of the halo of galaxies. In all cases, the correlation is stronger for red clusters than for blue ones. This result is used when considering the role of globular clusters in galaxy formation models.

Harris [11] presents a catalog of the GCS around 422 galaxies, of which 248 are E galaxies, 93 are S0 galaxies, and 81 are spiral and irregular galaxies. We studied the correlation between the total number of globular clusters and the dynamic mass of the host galaxy and found a relationship in the form $M_{dyn} = 4\sigma_e^2 R_e/G$, were σ_e is the dispersion of the central velocity, R_e - is the effective radius of the illumination profile of the galaxy. Also presented are updated versions of the specific frequency S_N of the globular clusters and the specific mass S_M depending on the luminosity of the host galaxy. These graphs show that either dwarf galaxies or supergiants have the highest values of specific frequency or specific mass. But in the middle range, the specific frequency S_N takes on a value of about 1 or a specific gravity of about 0.1. The authors conclude that the efficiency of globular cluster formation is most proportional to the halo mass of the host galaxy.

In [12], various properties of the GCS around early-type galaxies were studied. Possible models for the formation of globular clusters and their host galaxies are discussed. It is concluded that dwarf galaxies play an important role in the formation of the hierarchical clustering of the GCS.

Deep images of the GCS around 10 low-density galaxies were obtained using the Hubble Space Telescope [13]. The main properties of the GCS are studied to study the role of the environment in the formation and evolution of host galaxies. As the luminosity of the host galaxy decreases, the color bimodality of the globular cluster disappears faster. Here are the main results of this work: 1) in the environment, the mass of the host galaxy affects the properties of the GCS; 2) during the formation of the GCS, the influence of the environment is secondary; 3) globular cluster formation should be regulated by general physical processes in different environments.

The first list of GCS containing 60 systems was published in 1991 by Harris [14]. In [15], this list was brought up to 82 systems, in [16], to 252 systems, and in [11], their number confidently reached about 400 objects, taking into account some repetitions.

Note that prior to our works [17-19], there was no analysis of the available very extensive observational data in the literature, reliable empirical relationships between their main physical parameters were not found, and the classification of GCS was not developed. So there are still no attempts to determine some of the kinematic and dynamic parameters of these systems and a reliable theory of their origin and evolution within a specific scenario.

In [17], the analysis of observational data and the search for empirical dependences were carried out on the basis of our consolidated catalog [16] of 252 GCS. At the same time, due to the insufficiency for statistical processing of spiral, irregular, and dwarf galaxies by the GCS, the indicated study in [17] was carried out only for elliptical and lenticular galaxies. Therefore, we significantly expanded our union catalog and published the latest data in [18]. In [19], we managed to perform the first analysis of observational data for spiral and dwarf galaxies. However, within the framework of our consolidated catalog [18] of 441 GCS, such work for elliptical, lenticular, and irregular galaxies has not yet been carried out. Below we present the main results of the statistical analysis of the new catalog for all types of galaxies.

II. ABOUT THE CONTENTS OF THE CATALOG GCS

We managed to expand the catalog [16], both horizontally and vertically, bringing the number of GCS up to 441. This catalog contains the following characteristics of the GCS and their parent galaxies: the serial number of the GCS; the number of the parent galaxy according to NGC or another catalog; morphological type of the parent galaxy; right ascension and declination given for the year 2000; radial velocity of the galaxy; redshift; distance module; absolute magnitude of the parent galaxy; the number of globular clusters in the system; metallicity of GCS; specific frequency; links to published sources. Unfortunately, the literature does not contain complete data on the values of the masses, sizes of the GCS, and ages of host galaxies. On the basis of the GCS catalog compiled by us, we conducted an analysis in order to find possible statistical patterns.

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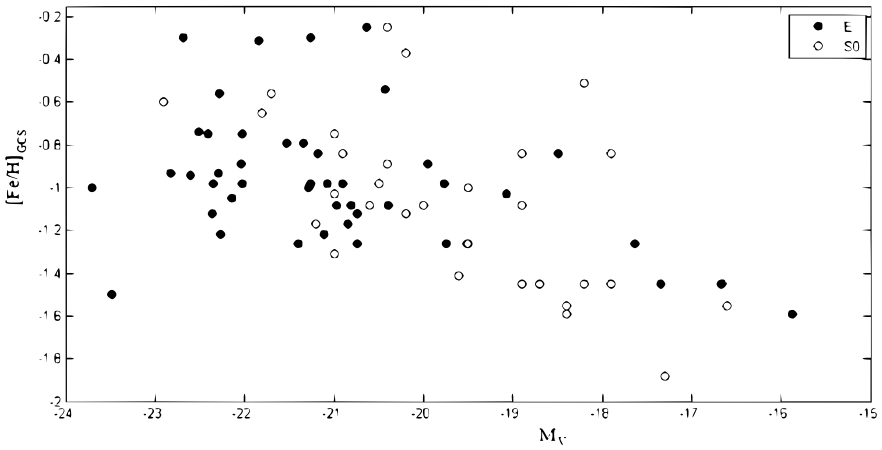


FIG. 1. Dependence of the GCS metallicity on the absolute magnitude of the host galaxy (light circles for S0 galaxies, dark circles for E galaxies).

The total number of elliptical galaxies in relation to spiral galaxies is more by about $N_E/N_S = 3.8$. In percentage terms, in our catalog [17], the ratio of galaxy types has the following form:

$$E : (S0 + SB0) : (S + SB) : Irr = 54 : 26 : 14 : 6, \tag{1}$$

moreover, the ratio of the number of elliptical galaxies to the number of all other types of galaxies is 1.16. At the same time, with an increase in the value of the compression of elliptical galaxies, their number decreases on average.

Table 1 below gives a percentage comparison of the types of galaxies in our composite catalog with other works.

TABLE I. Comparison of available GCS catalogs.

	Number of GCS	E	S0+SB0	S+SB	Irr
In [1]	60	57	15	23	5
In [2]	82	69	11	17	3
In [3]	252	54	35	9	2
In [4]	422	58	23	13	6
In our work [18]	441	54	26	14	6

The results of the comparison show that each time among the types of galaxies containing the GCS, a large proportion falls precisely on elliptical galaxies. But, if we distinguish the types of En separately, then S0 galaxies are in the lead, and then E0, E1, E3, E4, SB0, and so on. In contrast to works [14, 15], our percentage of lenticular galaxies dominates over spiral galaxies. This fact is explained mainly by the results of observations of the Hubble Space Telescope used by us, which also carried out observations of lenticular galaxies.

III. DEPENDENCES OF METALLICITY ON THE ABSOLUTE MAGNITUDE

From the point of view of the physics of the GCS, it is important to determine the dependence of their metallicity on the absolute magnitude of the host galaxy. Figure 1 shows the dependence for elliptical and lenticular galaxies as an example.

An analysis of observational data for individual types of galaxies shows that the metallicity depends linearly on the absolute magnitude of the host galaxy:

$$[Fe/H] = -2.91\,(\pm 0.42) - 0.09\,(\pm 0.02)\,M_V(forE - galaxy), \tag{2}$$

$$[Fe/H] = -4.22\,(\pm 0.79) - 0.16\,(\pm 0.04)\,M_V(forS0 - galaxy). \tag{3}$$

It should be noted that, for lenticular galaxies, the authors of [20] were first interested in the dependence of the metallicity of the GCS on M_V. Such dependence found by these authors is close to (3).

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However, for a relatively accurate determination of this dependence for spiral and dwarf galaxies, there are still relatively few observational data on the GCS metallicity. Despite this, we tried to evaluate this dependence and found that

$$[Fe/H] \approx -8.84\,(\pm 2.43) - 0.36\,(\pm 0.11)\,M_V(forS - galaxy). \tag{4}$$

$$[Fe/H] \approx -3.93\,(\pm 0.25) - 0.15\,(\pm 0.01)\,M_V(fordE - galaxy). \tag{5}$$

For irregular galaxies, the determination of the dependence of the metallicity of the GCS on the absolute magnitude of the host galaxies has not yet been possible due to a clear lack of observational data.

The dependences we found show that the brighter or greater the absolute magnitude of the host galaxy, the higher the metallicity of the GCS grows on average. The errors in determining the coefficients in these ratios are quite acceptable.

IV. DEPENDENCES OF THE NUMBER OF GLOBULAR CLUSTERS ON THE ABSOLUTE MAGNITUDE

An analysis of the dependence of the absolute magnitude of the host galaxy on the number of GCS shows that with an increase in the number of clusters in the globular cluster in the system, the value of the absolute magnitude increases, i.e. the greater the number of globular clusters, the brighter the parent galaxy. An analysis of the dependence of the absolute magnitude of the host galaxy on the number of globular clusters in elliptical and lenticular galaxies shows that there is a correlation between these parameters. We have found a logarithmic relationship between these parameters for different types of galaxies separately. It turned out that for elliptical galaxies

$$\lg N_{GC} = -4.48\,(\pm 0.22) - 0.35\,(\pm 0.01)\,M_V, \tag{6}$$

and for lenticular -

$$\lg\, N_{GC} = -6.27\,(\pm 0.50) - 0.42\,(\pm 0.03)\,M_V. \tag{7}$$

Obviously, for spiral, dwarf, and irregular galaxies, the values of their absolute magnitude must also correlate with the number of globular clusters in the system. Figure 2 shows the dependences of the absolute magnitude on the number of globular clusters in the GCS for spiral, dwarf and irregular types of galaxies. The calculation of statistical dependencies shows that

$$\lg N_{GC} = -3.43\,(\pm 0.46) - 0.27\,(\pm 0.02)\,M_V(forS - galaxy), \tag{8}$$

$$\lg N_{GC} = -2.79\,(\pm 0.34) - 0.24\,(\pm 0.02)\,M_V(fordE - galaxy), \tag{9}$$

$$\lg\, N_{GC} = -2.365\ (\pm 0.706)\ - 0.195\ (\pm 0.045)\ M_V(forIrr - galaxy), \tag{10}$$

From these dependences, we can confidently say that each time the greater the number of clusters in the GCS, the brighter the absolute magnitude of the host galaxy found from observations is.

V. OTHER EMPIRICAL DEPENDENCES

We have analyzed the statistical dependence of the number of GCS (N) in elliptical galaxies with a given compression value n on the degree of this compression itself. At the same time, using the least squares method, we found the following empirical dependence of N on the compression of elliptical galaxies n:

$$N = 39.04\ (\pm 4.03) - 3.95\,(\pm 0.80)\ n, \tag{11}$$

We were also interested in the dependence of the number of GCS of dwarf elliptical galaxies on the degree of compression:

$$N = 15.21\,(\pm 2.97) - 1.38\,(\pm 0.59)\,n \tag{12}$$

As can be seen, in both cases ((11) and (12)) the number of elliptical galaxies decreases as the degree of their compression increases within the linear law.

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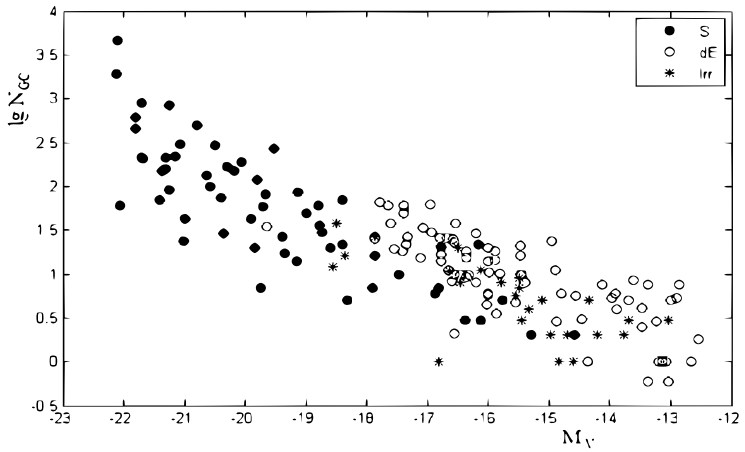


FIG. 2. Dependence between the logarithm of the number of globular clusters and the absolute magnitude of the host galaxy GCS (light circles for dE galaxies, dark circles for S galaxies, stars for Irr galaxies).

An analysis of the distribution of the average number of the most globular clusters in elliptical galaxies of a given type shows that with an increase in the compression of an elliptical galaxy, the logarithm of the average number of clusters in them decreases on average. Using the least squares method, we found this dependence in the form

$$\lg < N_{GC} > \ = 3.83\,(\pm 0.14) - 0.23\,(\pm 0.03)\,n \tag{13}$$

An analysis of the data on spiral galaxies shows that, at first glance, GCS are contained in almost all types of S galaxies, with almost 50 persent of these objects being mainly Sb, Sc, SBb, and Sbc galaxies. On the contrary, spiral galaxies of the Sd, Sdm, Sm, SBa, SBab, SBcd, and SBdm types either almost do not contain GCS in the form of a system, or contain them within the detection errors. In order to find out the dependence of the degree of richness of the GCS clusters on the type of galaxy, let us consider the distribution by types of the average number of objects in the system. From this we also conclude that for normal spiral galaxies, as the degree of twisting of the spiral arms increases, the average number of globular clusters in them clearly increases gradually:

$$\lg < N_{GC} >= 2.95\,(\pm 0.25) - 0.24\,(\pm 0.06)\,T_n \tag{14}$$

where T_n means the HyperLeda normal spiral galaxy type encoding value. This effect may be partly due to the fact that the detection of clusters for the case of wide open spiral arms differs from the case of tightly wound arms. So far, we have not been able to determine explicitly and with sufficient accuracy the dependence of $< N >$ on the value of the code of specific types of barred spiral galaxies (SB).

Next, we tried to obtain the dependence of the absolute magnitude M_V on the value of the type code for all spiral galaxies T in general. So we got the following:

$$M_V = -22.00\,(\pm 0.50) + 0.50\,(\pm 0.09)\,T \tag{15}$$

Here, although the coefficient in front of T has a not very desirable error in the bracket, but in general, the pattern is quite clear. This dependence should also be determined for normal and bar-like galaxies separately. So we got, respectively:

$$M_V = -22.57\,(\pm 0.62) + 0.61\,(\pm 0.13)\,T(forS - galaxy), \tag{16}$$

$$M_V = -20.84\,(\pm 0.89) + 0.35\,(\pm 0.14)\,T(forSB - galaxy). \tag{17}$$

As can be seen, this type of dependence for S and SB galaxies differs significantly.

Note that all dependences for spiral galaxies have been found for the first time, but from the analysis of specific quantities and the determination of the necessary dependences, unfortunately, we still have some dissatisfaction with the values of individual quantities for many GCS of spiral galaxies, since it is clear that they are found from observations approximately.

VI. TO THE THEORY OF THE ORIGIN OF THE POOR GCS

The main idea about the theory of the origin of the GCS was proposed by us for the first time in [21] and consists in using the analogy of stellar systems and gas systems with the adiabatic exponent γ equal to 5/3. The application of this analogy once made it possible to apply certain results on the gaseous medium to purely stellar systems (see, for example, [22]).

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Therefore, this method can also be used in reverse order, i.e. having theoretical results for a spherical stellar system, one can apply them to some extent to a spherical gas system with $\gamma = 5/3$ in order to at least very approximately study the initial state, which is responsible for the formation of the GCS, i.e. try to analyze the instability of the collapse of a protogalaxy with respect to specific perturbation modes, which naturally plays a certain role in the formation of a system of protoclusters.

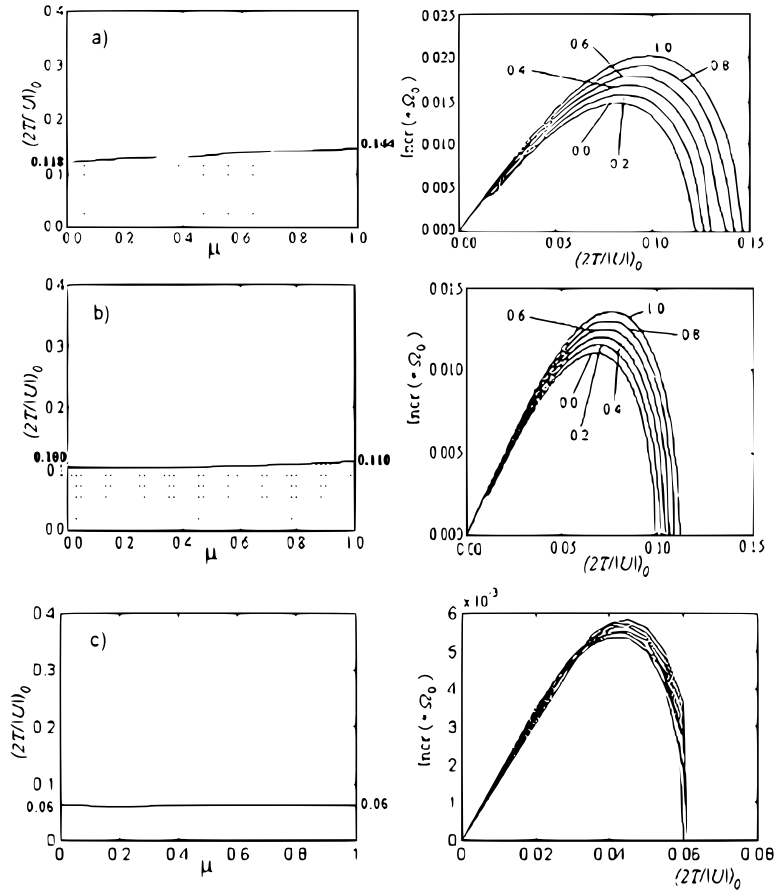


FIG. 3. Critical diagrams of dependence of the initial virial ratio on the rotation parameter and the corresponding values of the instability increment at m=1: a) N=9, n=7: b) N=11, n=9, c) N=18, n=16.

As we know, globular clusters are the oldest objects in galaxies, and therefore we can assume that their protoclusters can form during the period of protogalaxy collapse. This requires an analysis of the instability of the perturbation against the background of a collapsing, nonstationary model of a spherical system. Then the following question arises: what should be the physical state in the initial period before the onset of the instability of the gravitational collapse in order for the instability that leads to the formation of relatively poor GCS to begin? Such a problem, in turn, requires an analysis of the instability of individual oscillation modes against the background of a collapsing, and in the general case, from the point of view of theory, a radially pulsating model of a nonlinearly nonstationary spherical system. As a collapsing model, we take a non-linear non-stationary generalization of Einstein's equilibrium spherical configuration. Such a generalization of the equilibrium Einstein ball to the case of nonlinear nonstationarity with rotation was performed in the works [23-24].

Considering the perturbation of the potential, which depends on the Legendre function, in the form

$$A(\psi)\, r^N \exp(im\theta) P_n^m(\cos\theta), \tag{18}$$

one can find the following non-stationary dispersion equation (NDE) in the general case [24]:

$$\begin{aligned} A(\psi) \;=\; & \frac{3(N-n-2)!!(N+n-1)!!}{\Pi^3(\psi)} \left[\sum_{s=0}^{N-1} \sum_{k=N-1-s}^{N-1} \frac{2^{-k} s! C_{ks} [N(s+1)+s-1-(n-1)(n+2)]}{(k/2)![(N-s-1)/2]!(s-n+1)!!(s+n+2)!!} Y_k + \right. \\ & + \left. im\mu \sum_{s=0}^{N-2} \sum_{k=N-1-s}^{N-1} \frac{[(k-1)/2]! s! C_{ks} [N(s+1)+2(s-1)-(n-2)(n+3)]}{(k+1)![(N-s-2)/2]!(s-n+2)!!(s+n+3)!!} Y_k \right]. \end{aligned} \tag{19}$$

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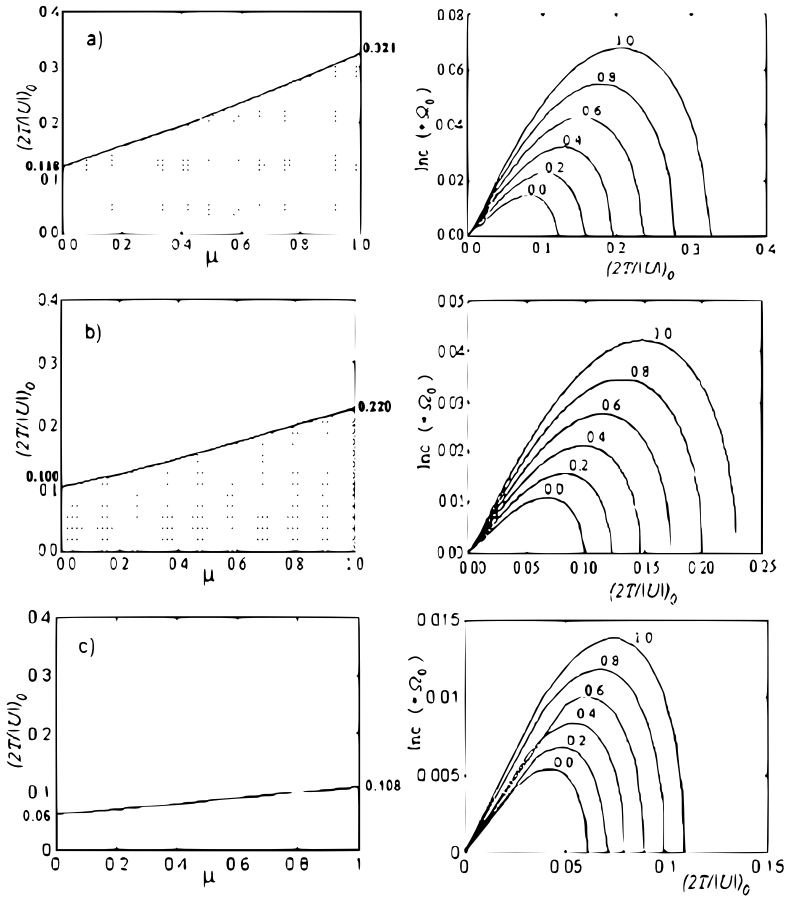


FIG. 4. Critical diagrams of dependence of the initial virial ratio on the rotation parameter and the corresponding values of the instability increment at the largest values of m for modes: a) N=9, n=7: b) N=11, n=9, c) N=18, n=16.

where is the time $t = (1-\lambda^2)^{-3/2}(\psi + \lambda \sin\psi)$, μ - rotation parameter $(0 \le \mu \le 1)$,

$$Y_k = \int_{-\infty}^{\psi} (H_\alpha + \frac{\nu_a}{r} H_\beta)^{N-1-k} (\frac{\nu_b}{r} H_\beta)^k \Pi^3(\psi_1) S(\psi, \psi_1) A(\psi_1) d\psi_1, \tag{20}$$

$\Pi(\psi)$ - compression or expansion function, $\lambda = 1 - \left(\frac{2T}{|U|}\right)_0$, $\left(\frac{2T}{|U|}\right)_0$ - virial parameter at the moment of instability onset, $S(\psi, \psi_1)$ - analogue of Green's function. The meaning of this analogue and all other designations, see, for example, in [24-25].

As can be seen from (19) and (20), the NDE is very cumbersome, and a detailed description of this equation for one fixed oscillation mode (N,n,m) takes several pages of text. If we talk about the method for solving such an NDE, then for a numerical solution, it is necessary first to go from the integral form (20) to the differential one and then integrate the system of differential equations by the method of stability of periodic solutions for given values of the parameters $\left(\frac{2T}{|U|}\right)_0$ and μ. The methods of transition to the differential form and integration of the NDE have been used by us many times before (see, for example, [24-25]).

If the number of globular clusters in the system is in the interval (10;100), then according to our classification of the GCS [14], we call such systems poor. Most of the dwarf elliptical galaxies are poor, and sometimes in some spiral galaxies you can also see such a picture. Therefore, in this article, we reviewed the analysis of poor GCS. Here we have studied cases of vibration modes (N=9, n=7) at m=1;4 and 7, (N=11, n=9) at m=1;5 and 9, and also (N=18, n =16) at m=1 and 16. For the specified modes of oscillations, instability under certain initial conditions can lead to the formation of a system of clusters, the number of which will correspond to the case of poor GCS.

The results of the numerical analysis of the NDE for the indicated oscillation modes in the form of a critical dependence of $\left(\frac{2T}{|U|}\right)_0$ on μ and values of instability increments in units of $\Omega_0 = \sqrt{\frac{4\pi G\rho_0}{3}}$ (ρ_0 - is the initial uniform density of the system) for various values of the virial parameter and μ are shown in Figure 3 and Figure 4, where graphs are given as an example for three

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vibration modes at the minimum and maximum values of m.

From this we can draw the following conclusions:

- as the modes of oscillations become smaller-scale, the corresponding regions of instability gradually narrow, and the characteristic time for the manifestation of these instabilities increases. In this case, rotation is always a destabilizing factor;

- it can be assumed that the mechanism of instability of radial orbits plays an important role in the formation of a system of protoclusters.

VII. CONCLUSION

In this work, we obtained the following results:

- a statistical analysis of the compiled consolidated catalog of 441 GCS was performed;

- the necessary histograms and diagrams were built for the main physical parameters of the GCS;

- a number of new empirical relationships have been found between the main physical parameters of the GCS and their parent galaxies for elliptical, lenticular, spiral, dwarf and irregular galaxies;

- proposed a possible theory of the origin of poor GCS around galaxies.

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