DOI 10.1007/s10511-015-9374-9
Astrophysics, Vol. 58, No. 2, June, 2015

GLOBULAR STAR CLUSTER SYSTEMS AROUND GALAXIES. II. SPIRAL AND DWARF GALAXIES

I. U. Tadjibaev, S. N. Nuritdinov, and J. M. Ganiev

Our composite catalog of globular cluster systems (GCS), which was studied in part I [1] of this paper , has been substantially extended because of a lack of data in it for use in searches for empirical relationships between the physical parameters of GCS of spiral and dwarf galaxies taking the characteristics of the parent galaxies into account. For the first time a number of empirical relationships are found for GCS of spiral and dwarf galaxies. These results differ significantly from the analogous relationships for GCS of elliptical and lenticular galaxies [1]. A possible new approach to the theory of the origin of poor GCS, which take a large part of the list of GCS of dwarf and spiral galaxies, is proposed.
Keywords: *galaxies: systems of globular star clusters*

1. Introduction

In part I [1] of this paper , a search was made for empirical relationships among the major physical parameters for globular cluster systems (GCS) of elliptical and lenticular galaxies based on a composite catalog of GCS that we composited from data accumulated up to 2010 and possible variants of a general classification for these systems were given. But because of a data insufficient for statistical analysis of GCS of spiral, irregular, and dwarf galaxies, however, this kind of effort has not yet been undertaken for these systems. Over the last few years there has been greatly increased interest in GCS [2-5]. The detailed work of Harris, et al. [5], in collecting these data is especially

Department of Astronomy and Atmospheric Physics, National University of Uzbekistan; e-mail: nur200848@mail.ru, tadj_ikram@mail.ru

Original article submitted December 24, 2014; accepted for publication April 10, 2015. Translated from Astrofizika, Vol. 58, No. 2, pp. 197-208 (May 2015).

noteworthy.

With these data and by careful comparison of them, we have expanded our earlier composite catalog (described in Ref. 1) and recently published it in the form of a revised second composite catalog [6] that includes the available data on GCS obtained worldwide through 2013.

When we were preparing the earlier article [1] we had data on only 24 spiral and 5 irregular galaxies, while today's list [6] contains 61 spiral galaxies but only 23 irregular galaxies. Thus, it is entirely appropriate to search now for empirical dependences for GCS of spiral galaxies, and, rather than search for such dependences among the irregular galaxies (because this amount of data is still insufficient), to do the analysis for GCS of dwarf galaxies, since the number of the latter in today's list [6] has already reached 85. In addition to this, the spiral and dwarf galaxies have one feature in common: in them, GCS are clearly diffuse compared to elliptical and lenticular galaxies. This fact has force us to discuss the origin of poor GCS below in this article.

2. GCS of spiral galaxies

Finding and identifying systems of globular clusters in spiral galaxies is an extremely complicated task. This sort of problem is solved relatively easily and confidently only if a spiral galaxy is viewed from the edge. Otherwise, the projection of a GCS onto the plane of the disk leads to a complicated pattern. In particular, that is why, in our composite catalog [6], only 14% belong to spiral galaxies; this represents 61 GCS, which are currently sufficient, in principle, to search for some patterns in their behavior.

We begin with a few words on publications about observations of GCS of spiral galaxies, since they cannot all be reasonably considered here and we are only interested for now in the statistics and in searching for possible patterns. The study of GCS of spiral galaxies clearly began with our galaxy, since the term "globular cluster system" is first encountered in the title of an article by Parenago [7] which gives values for the diameters of clusters, their stellar magnitudes, interstellar absorption, etc. The next, well studied object was the GCS M31 (early data and publications are reviewed in Ref. 8). The main list of articles on GCS that we have used can be found in Refs. 3-6. It is interesting that until 2000 only 14 GCS of spiral galaxies had been discovered and studied to some extent, and afterward, about 47. On looking at the content of our merged catalog [6], it can be seen that values of the masses, distances, number of globular clusters, radial velocities, absolute stellar magnitudes, etc., are given for almost all the GCS of spiral galaxies. For most of them, however, the metallicity, and the specific density and mass of the parent galaxy, are still unknown.

Figure 1 is a histogram of the distribution of the GCS with respect to the types of spiral galaxies. It shows at first glance that GCS are contained in nearly all types of S-galaxies, with almost 50% of these objects being mainly Sb, Sc, SBb, and Sbc galaxies. On the other hand, spiral galaxies of types Sd, Sdm, Sm, SBa, SBab, SBcd, and SBdm hardly contain GCS in the form of a system, or contain them only within the limits of error in their detection. In order to find a dependence of the degree of density of GCS clusters on the type of galaxy, we consider the distribution with respect to types of the average number of objects in a system (see Fig. 2). From this we find that for normal

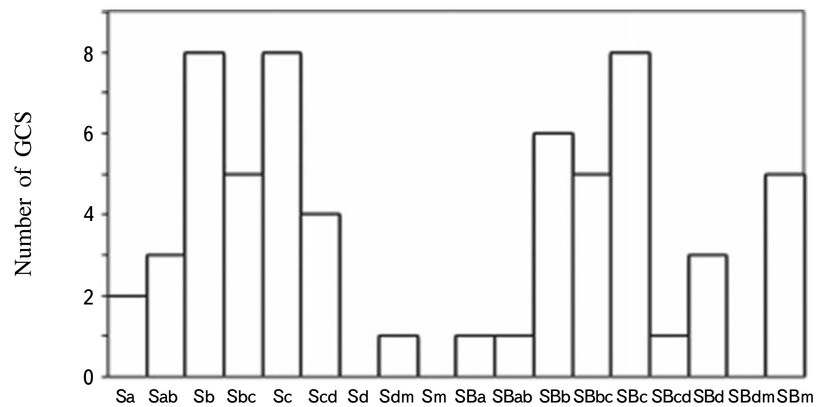

Fig. 1. Distribution of the GCS with respect to types of spiral galaxies.

spiral galaxies, as the degree of swirl of the spiral arms increases, the average number of globular clusters in them gradually increases:

$$\log\langle N_{GC}\rangle = 2.95(\pm 0.25) - 0.24(\pm 0.06)T_n\ , \tag{1}$$

where T_n denotes the Hyper Leda type code of a normal galaxy. This effect may be partly related to the fact that the detection of clusters in the case of wide open spiral arms is different from the case of tightly swirling arms. We have not yet been able to determine explicitly the dependence of $\langle N_{GC}\rangle$ on the code value for specific types of spiral galaxies with a bridge (SB).

It is evident that the absolute stellar magnitudes M_V must correlate with N_{GC}. Figure 3 suggests a correlation of this sort. A fit to this empirical dependence yields

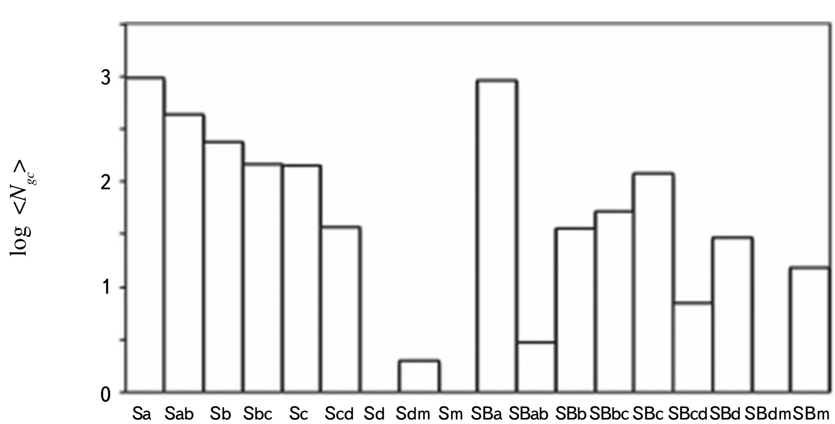

Fig. 2. Distribution of the average number of GCS in the spiral galaxies.

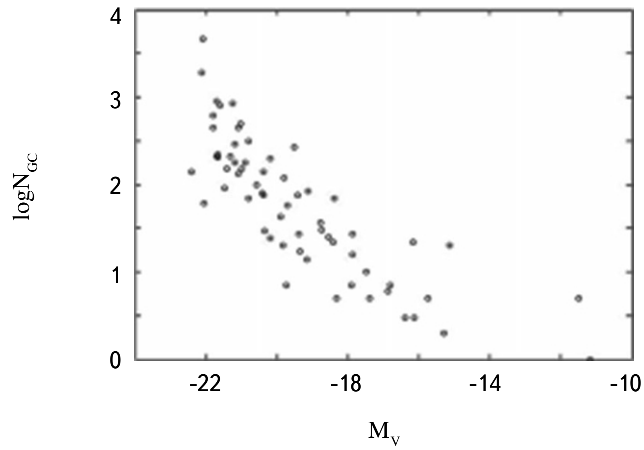

Fig. 3. The relationship between the logarithm of the number of globular star clusters and the absolute stellar magnitude of the GCS of the parent galaxy for spiral galaxies.

$$\log N_{GC} = -3.43(\pm 0.46) - 0.27(\pm 0.02) M_V \,. \tag{2}$$

On comparing the empirical Eq. (2) with the analogous equation for elliptical and lenticular galaxies [1] we conclude that there is a substantial difference in the coefficients for these formulas. On the other hand, it is possible to try to obtain a dependence of the absolute stellar magnitude M_V on the value of the type code T for all the spiral galaxies as a whole. This yielded the following:

$$M_V = -22.00(\pm 0.50) + 0.50(\pm 0.09) T \,. \tag{3}$$

Although the spread in the coefficient of T indicated in parentheses is not highly desirable, the behavior is quite distinct. This dependence should also be determined separately for normal and bar galaxies. For these we found, respectively,

$$M_V = -22.57(\pm 0.62) + 0.61(\pm 0.13) T \,, \quad \text{(S- galaxies)} \tag{4}$$

$$M_V = -20.84(\pm 0.89) + 0.35(\pm 0.14) T \,. \quad \text{SB-galaxies)} \tag{5}$$

Finally, we now consider separately the relationship between M_V and metallicity. At present the metallicity [Fe/H] is only known for a few GCS. Nevertheless, it was interesting to calculate this dependence for future orientation. We found

$$[\mathrm{Fe/H}] \approx -8.84(\pm 2.43) - 0.36(\pm 0.11) M_V \,,$$

which requires further refinement in the future. A comparison of this dependence with the analogs for normal and elliptical galaxies shows that the behavior of [Fe/H] with M_V (see Eq. (6) of Ref. 1) is almost the same, but the coefficients differ substantially.

The following should be noted: (1) a search for any kind of statistical dependence of the specific density S_N [1] on any of the other parameters of GCS and the parent galaxies yielded no satisfactory result, and (2) after an analysis of the specific values and a determination of the necessary dependences, the values of the individual quantities (especially N_{GC}) for many GCS of spiral galaxies are still not satisfactory, since they have been determined approximately and unreliably from the observations. As an example, it is sufficient to point out that for NGC 4594 (the "Sombrero") the value of N_{GC} is given as 1550±500 in Ref. 9 and as 1900 in Ref. 10.

3. GCS of dwarf galaxies

Of the various types of galaxies, dwarf galaxies appear to be generally the most widely distributed in the universe. They are mainly encountered in elliptical (dE) and sometimes in spheroidal (dSph), irregular (dIr), spiral (dS), and blue compact (dBC) forms. Our catalog of 441 GCS contains 85 dwarf galaxies, of which $\approx 90\ \%$ are dE galaxies. For that reason we limit ourselves in the following to a search for empirical relationships among elliptical dwarf galaxies containing GCS.

We begin the analysis with a search for an empirical dependence of the number of GCS of dwarf elliptical galaxies on the degree of compression n_e of the parent galaxy. Note that the number N_S of discovered GCS with respect to the types of dwarf galaxies (more precisely, with respect to n_e) is distributed somewhat nonuniformly. This is primarily because of the errors in determining n_e from observations. If we are interested in a linear dependence $N_S(n_e)$, then the data of Ref. 6 yield

$$N_S = 15.21(\pm 2.97) - 1.38(\pm 0.59) n_e \,, \tag{6}$$

i.e., on the average, the number of GCS of dwarf elliptical galaxies decreases with increasing compression, as in the case of normal elliptical galaxies [1]. It is interesting that, as opposed to normal elliptical galaxies, in the case of dwarf galaxies elliptical ones with $n_e = 7$ are also observed.

It turned out to be somewhat more difficult to determine the statistical dependence of the average number $\langle N_{GC} \rangle$ of globular clusters, as such, on the compression n_e. The reason is that the N_{GC} values have a very large error. However, there is a corresponding dependence for GCS of normal elliptical galaxies with sufficient accuracy [1]. Thus, we need to refine the analogous data (n_e, N_S) for dwarf galaxies in the future.

Figure 4 shows a plot of the relationship of absolute stellar magnitude of the parent galaxy to the number of globular clusters in GCS. There is clear correlation between these two parameters. A least squares fit yields a linear dependence between $\log N_{GC}$ and M_V of the form

$$\log N_{GC} = -2.79(\pm 0.34) - 0.24(\pm 0.02) M_V \,. \tag{7}$$

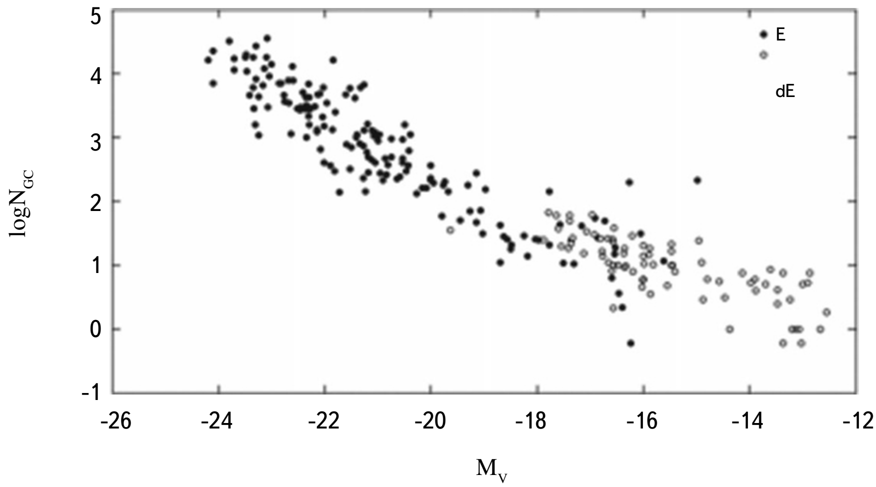

Fig. 4. Relationship between the absolute stellar magnitude of a parent galaxy and the logarithm of the number of globular clusters (hollow circles for dE-galaxies, solid circles for E-galaxies).

Here the errors in determining the coefficients are quite acceptable.

On the other hand, there is some interest in studying the possible dependence of the absolute magnitude M_V on the metallicity of GCS. There are, however, relatively few observational data available now for a comparatively accurate determination of this dependence. Nevertheless, we have attempted to estimate this dependence and we found that

$$[\mathrm{Fe/H}] \approx -3.93(\pm 0.25) - 0.15(\pm 0.01) M_V \,. \tag{8}$$

Finally, there is a also need for an analysis of the dependences examined here in terms of the new catalog [6] for GCS of elliptical galaxies in two cases: with and without taking dE galaxies into account. Thus, for elliptical galaxies as a whole (i.e., also including dwarf dE galaxies) we find the following empirical dependences:

$$N_S = 39.04(\pm 4.03) - 3.95(\pm 0.80) n_e \,, \tag{9}$$

$$\log\langle N_{GC}\rangle = 3.83(\pm 0.14) - 0.22(\pm 0.03) n_e \,, \tag{10}$$

$$\log N_{GC} = -4.48(\pm 0.22) - 0.35(\pm 0.01) M_V \,, \tag{11}$$

$$[\mathrm{Fe/H}] = -2.91(\pm 0.42) - 0.09(\pm 0.02) M_V \,. \tag{12}$$

On excluding the dwarf galaxies, for the normal elliptical galaxies we find in terms of the new extended catalog that

$$N_S = 23.25(\pm 1.89) - 2.50(\pm 0.38)n_e\,, \tag{9'}$$

$$\log\langle N_{GC}\rangle = 3.99(\pm 0.15) - 0.20(\pm 0.03)n_e\,, \tag{10'}$$

$$\log N_{GC} = -5.92(\pm 0.35) - 0.42(\pm 0.02)M_V\,, \tag{11'}$$

$$[\mathrm{Fe/H}] = -1.15(\pm 0.86) - 0.01(\pm 0.04)M_V\,. \tag{12'}$$

A comparison of the three cases examined above shows that the physical properties of dwarf dE galaxies differ clearly from the corresponding properties of normal elliptical galaxies.

We note that an analysis of the correlation of the specific density S_N with the other parameters of a GCS and a parent galaxy revealed no statistical relationship of any kind, as in the case of spiral galaxies.

4. An approach to the theory of the origin of poor GCS

Without going into the old controversy between the hierarchical and cascade theories of the origin of galaxies, but assuming that both these theories may, in principle, be applicable, depending primarily on the scale being considered, we describe a possible approach to the theory of the formation of relatively poor GCS.

We first proposed the basic idea behind this approach in Ref. 11. It involves using an analog of stellar systems and gas systems with an adiabatic index γ equal to 5/3. In its time this analogy made it possible to apply some results for gaseous media to purely stellar systems [12]. Thus, this method can also be used in reverse order, i.e., given some theoretical results for a spherical stellar system, they can be applied to some extent to a spherical gas system with $\gamma = 5/3$ in order to study, at least approximately, the initial state responsible for the formation of a GCS, i.e., the model can be used to try to analyze instability in the collapse of a protogalaxy with respect to certain perturbation modes that play a decisive role in the formation of a protocluster system.

Globular clusters are the oldest objects in galaxies, so we have reason to assume that their protoclusters may have been formed during the collapse period of a protogalaxy; this requires analysis of the instability of the perturbation against the background of a collapsing, nonstationary model for the spherical system. The next question then arises: what sort of physical state must exist in the initial period before the onset of the gravitational collapse instability in order to produce the instability that leads to the formation of relatively poor GCS? This problem, in turn, requires an analysis of individual oscillatory modes against the background of a collapsing and, in general, radially oscillating theoretical model for a nonlinear nonstationary spherical system. For the model of the collapse we take a nonlinear nonstationary generalization of the Einstein equilibrium spherical configuration. This generalization of Einstein's equilibrium sphere to the nonlinear nonstationary case with rotation has been discussed by one of the authors [13,14].

A potential perturbation in terms of Legendre functions of the form

$$A(\psi) r^N \exp(im\theta) P_n^m(\cos\theta), \tag{13}$$

yields the following general expression for the nonstationary dispersion relation [14]:

$$A(\psi)=\frac{3(N-n-2)!!(N+n-1)!!}{\Pi^3(\psi)}\left[\sum_{s=0}^{N-1}\sum_{\substack{k=N-1-s\\(k-\text{even})}}^{N-1}\frac{2^{-k}\, s!\, C_{ks}\left[N(s+1)+s-1-(n-1)(n+2)\right]}{(k/2)!\left[(N-s-1)/2\right]!(s-n+1)!!(s+n+2)!!}Y_k+\right.$$
$$\left.+im\mu\sum_{s=0}^{N-2}\sum_{\substack{k=N-1-s\\(k-\text{odd})}}^{N-1}\frac{\left[(k-1)/2\right]!s!C_{ks}\left[N(s+1)+2(s-1)-(n-2)(n+3)\right]}{(k+1)!\left[(N-s-2)/2\right]!(s-n+2)!!(s+n+3)!!}Y_k\right], \tag{14}$$

where the time $t=\left(1-\lambda^2\right)^{-3/2}(\psi+\lambda\sin\psi)$, μ is the rotation parameter ($0\le\mu\le1$),

$$Y_k=\int_{-\infty}^{\psi}\left(H_\alpha+\frac{\upsilon_a}{r}H_\beta\right)^{N-1-k}\left(\frac{\upsilon_b}{r}H_\beta\right)^{k}\Pi^3(\psi_1)S(\psi,\psi_1)A(\psi_1)d\psi_1, \tag{15}$$

$\Pi(\psi)$ is the compression or expansion function, $\lambda=1-\left(2T/|U|\right)_0$, $\left(2T/|U|\right)_0$ is the virial parameter at the time of onset of the instability, and $S(\psi,\psi_1)$ is an analog of the Green function. The significance of this analogy and the other notation are discussed in Refs. 14 and 15.

It can be seen from Eqs. (14) and (15) that the nonstationary dispersion relation is extremely cumbersome and a detailed description of this equation for a single oscillatory mode (*N, n, m*) would fill several pages of text. As for ways of solving this kind of nonstationary dispersion relation, for a numerical solution it is first necessary to transform from the integral form (15) to a differential form and then integrate the system of differential equations using the stability technique for periodic solutions with set values of the parameters $\left(2T/|U|\right)_0$ and μ. We have used methods for the transformation to a differential form and integration of the nonstationary dispersion relation many times [14,15].

In accordance with our classification of GCS [1], we refer to these systems as diffuse if the number of globular clusters in them lies in the range of (10; 100). The bulk of the dwarf elliptical galaxies are poor, and sometimes a pattern of this sort can be seen in some spiral galaxies. Thus, for this article we have decided to begin the analysis with the case of poor GCS. Here we have studied oscillatory modes (N = 9, n=7) with m = 1; 4 and 7 (N = 11, n = 9) for m = 1; 5 and 9, as well as (N = 18, n = 16) for m = 1 and 16. For these modes, with certain initial conditions the instability is capable of causing the formation of a system of bunches, the number of which will correspond to the case of poor GCS.

Figures 5 and 6 show the results of a numerical analysis of the nonstationary dispersion relation as plots of the critical dependence of $\left(2T/|U|\right)_0$ and μ and of the instability increments in units of $\Omega_0 = \sqrt{4\pi G \rho_0/3}$ (ρ_0 is the initial uniform density of the system) for different values of the virial parameter and μ. Also shown there as an example are plots for three oscillatory modes with minimum and maximum values of m.

This yields the following conclusions:

A. When the modes are on a finer scale, the corresponding instability regions gradually become narrower and

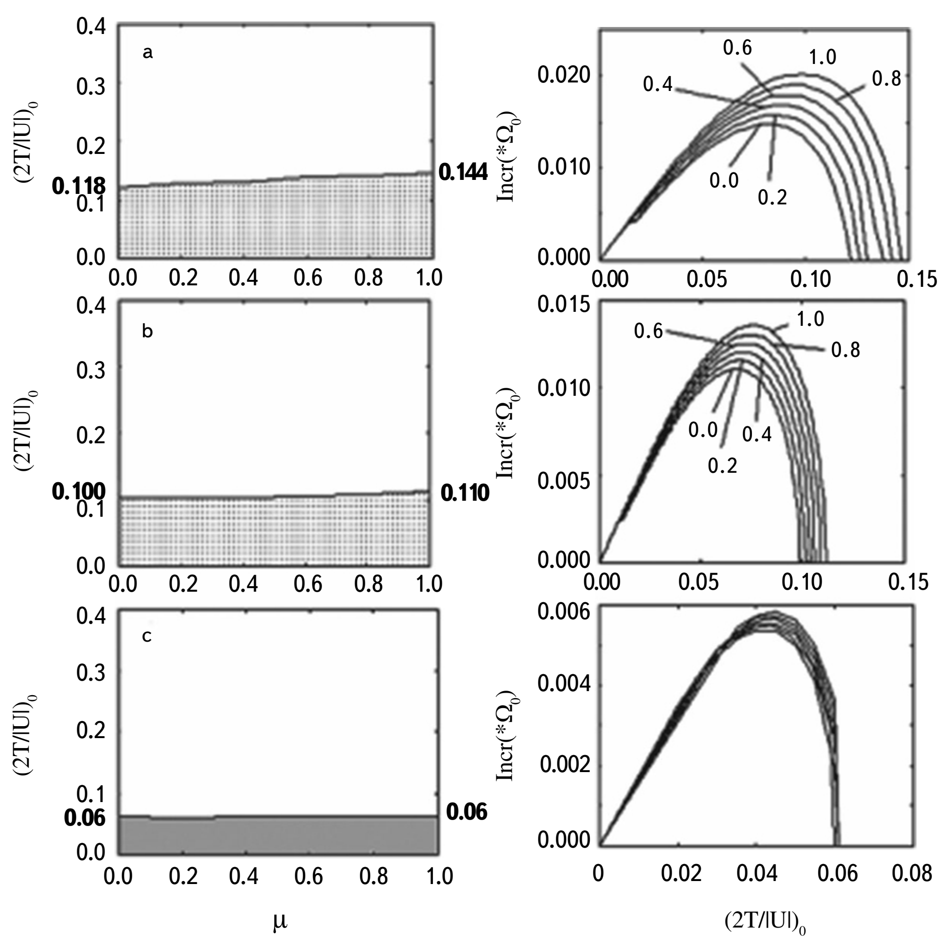

Fig. 5. Critical diagrams showing the dependence of the initial virial ratio on the rotation parameter and the corresponding values of the instability growth rate for m = 1: a) N = 9, n = 7: b) N = 11, n = 9, c) N = 18, n = 16.

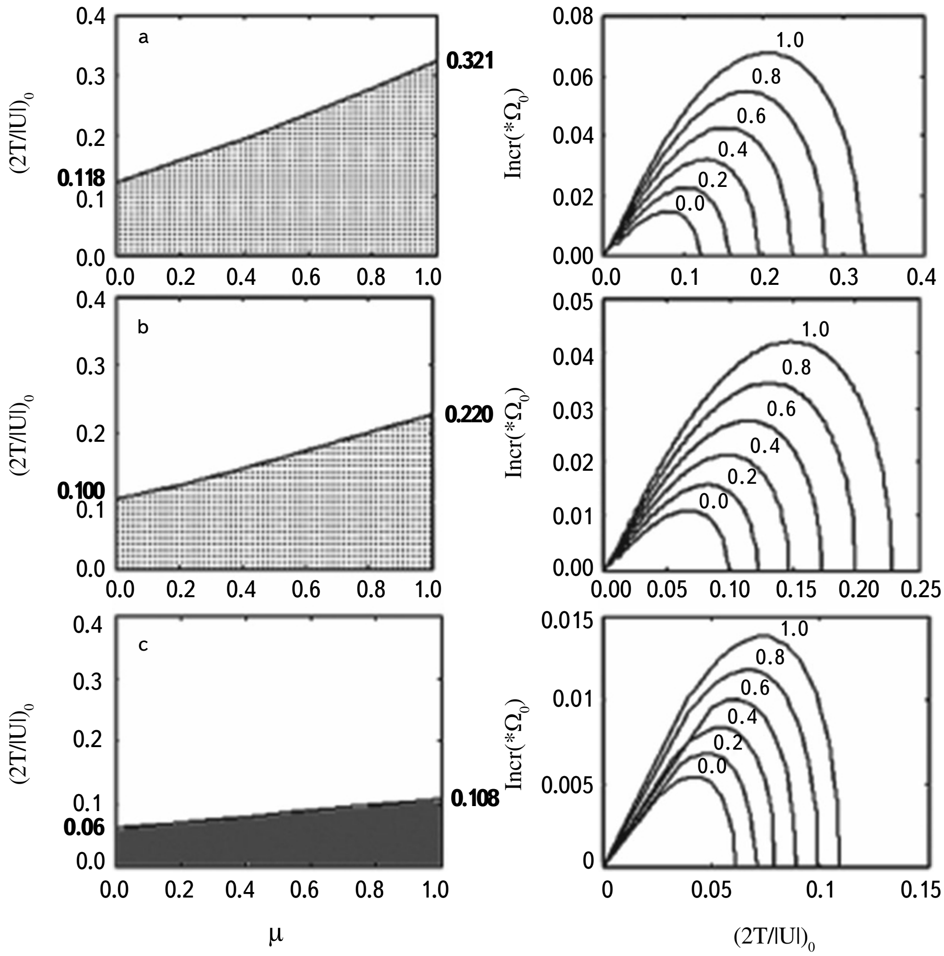

Fig. 6. Critical diagrams showing the dependence of the initial virial ratio on the rotation parameter and the corresponding values of the instability growth rate at small values of m for the modes (a) $N = 9$, $n = 7$; (b) $N = 11$, $n = 9$; (c) $N = 18$, $n = 16$.

the characteristic time for appearance of these instabilities increases. Here, rotation is always a destabilizing factor.

B. With increasing azimuthal wave number *m*, the instability region on the $\left(2T/|U|\right)_0 \div \mu$ diagram also gradually increases.

C. It can be assumed that the mechanism of radial orbit instability plays an important role in the formation of protocluster systems.

D. A comparison of the calculations for the oscillatory modes studied here shows that, on the average, an instability sets in when the total kinetic energy of the system in the initial state is less than 4% of the potential energy.

5. Conclusion

We have obtained the following results in this paper:

1. In order to study the statistical and physical properties of GCS of spiral and dwarf galaxies, our latest catalog, which was studied in detail in the first part of this article [1], has been supplemented with new observational data after comparison with data from various authors [6].

2. Observational data for GCS of spiral and dwarf galaxies are analyzed statistically for the first time. This analysis was based on data for GCS of 61 spiral and 85 dwarf galaxies; the required diagrams and histograms for their major physical parameters have been constructed and studied. In particular, the dependence of the number of clusters in GCS of spiral galaxies on their type codes has been found and, for dwarf galaxies, the dependence of the number N_{GC} on the compression *n*. It turns out that dE7 elliptical galaxies are also found among the dwarf galaxies.

3. The statistical dependences of the parameters N_{GC} and [Fe/H] on the absolute stellar magnitude M_V of the parent galaxies have been obtained and studied separately for GCS of spiral and dwarf galaxies. An acceptable dependence of M_V on type code for spiral galaxies has also been found.

4. A possible new approach to the theory of the origin of poor GCS has been proposed which is certainly an approximation, since it uses an analogy between spherical stellar systems and a gas with an adiabatic index of 5/3. The corresponding model calculations are carried out, the critical $\left(2T/|U|\right)_0 \div \mu$ diagrams are constructed, and the corresponding values of the instability growth rate are calculated for some specific small-scale oscillatory modes.

This work was supported by grant No. F-2-54 of the Committee for the Coordination of the Development of Science and Technology of the Republic of Uzbekistan (KKRNT-RUz).

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