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БАЯНДАМАЛАРЫ

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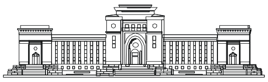

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RESPONSE OF THE ISOTROPIC HERNQUIST SPHERE TO FLATTENING OF ITS SPATIAL STRUCTURE

Abstract. Elliptical galaxies are interesting objects to study, as the mechanisms of their formation, evolution and stability are still unclear. In addition to the methods of observational astronomy, computer simulation methods have been actively developed and used in recent decades, in particular, to study galaxies as isolated collisionless systems. In this case, an important task is to find the equilibrium distribution function to determine the initial conditions of the system. One of the known distribution functions used to construct elliptical galaxies and dark matter halos is the Hernquist distribution function. This article examines the stability of a system constructed according to this distribution function with respect to perturbations introduced into the structure of particle distribution; the method used for generating the initial conditions is described; the density profiles for spherical and non-spherical systems are considered; a macroparameter D that characterizes the deviation of the perturbed system from certain state is introduced. The result of this work is the conclusion that, on the whole, after the introduction of disturbances, the system stabilizes, and the degree of the system's tendency to acquire the initial shape depends on the nature of the introduced disturbances and their magnitude. Density wave is observed, passing over time from the center of the system to the periphery. We can conclude that the isotropic Hernquist distribution is irreversible with respect to the introduced perturbations of its structure.

Key words: elliptical galaxies, Hernquist distribution, stability, perturbations, N-body simulation.

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ХЕРНКВИСТ ИЗОТРОПТЫ СФЕРАСЫНЫҢ КЕҢІСТІКТІК ҚҰРЫЛЫМДЫ ЖАНШЫЛУҒА РЕАКЦИЯСЫ

Аннотация. Эллиптикалық галактикаларға зерттеу жүргізу өте қызық, өйткені олардың қалыптасу, эволюция және тұрақтылық механизмдері әлі күнге дейін түсініксіз. Бақылау астрономиясының әдістерінен басқа, компьютерлік модельдеу әдістері соңғы онжылдықтарда белсенді дамып, қолданылып келеді. Соның бірі галактикаларды оқшауланған соқтығыссыз жүйелер ретінде зерттеу. Бұл жағдайда жүйенің бастапқы жағдайларын анықтау үшін тепе-теңдік бөлу функциясын табу маңызды міндет болып саналады. Эллиптикалық галактикалар мен қараңғы материя галосын құру үшін қолданылатын белгілі тарату функцияларының бірі – Хернквистің таралу функциясы. Бұл мақалада осы бөлу функциясына сәйкес құрылған жүйенің бөлшектердің таралу құрылымына енгізілетін бұзылуларға қатысты тұрақтылығы зерттеледі; бастапқы жағдайларды құру әдісі сипатталады; сфералық және сфералық емес жүйелер үшін тығыздық профильдері қарастырылады; d макропараметрі енгізілген жүйенің белгілі бір күйден ауытқуы сипатталады. Жұмыстың нәтижесінде авторлар: «тұтастай алғанда, бұзылулар енгізілгеннен кейін жүйе тұрақтанады және жүйенің бастапқы форманы алуға деген ұмтылыс дәрежесі енгізілген бұзылулардың сипатына және олардың магнитудасына байланысты» деген қорытындыға келеді. Уақыт өте жүйенің ортасынан периферияға өтетін тығыздық толқыны байқалады. Хернквистің изотропты таралуы оның құрылымының енгізілген бұзылыстарына қатысты қайтымсыз деп қорытынды жасауға болады.

Түйін сөздер: эллиптикалық галактикалар, Хернквистердің таралуы, тұрақтылық, ауытқулар, N-денені модельдеу.

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ОТКЛИК ИЗОТРОПНОЙ СФЕРЫ ХЕРНКВИСТА НА СПЛЮЩИВАНИЕ ЕГО ПРОСТРАНСТВЕННОЙ СТРУКТУРЫ

Аннотация. Эллиптические галактики являются интересными объектами для изучения, так как механизмы их формирования, эволюции и устойчивости до сих пор остаются неясными. Помимо методов наблюдательной астрономии в последние десятилетия активно развиваются и используются методы компьютерного моделирования, в частности, для изучения галактик как изолированных бесстолкновительных систем. При этом важной задачей является нахождение равновесной функции распределения для определения начальных условий системы. Одной из известных функций распределения, используемых для построения эллиптических галактик и гало темной материи, является функция распределения Хернквиста. В данной статье исследуется устойчивость системы, построенной согласно данной функции распределения, по отношению к вводимым возмущениям в структуру распределения частиц; описывается метод генерации начальных условий; рассматриваются профили плотности для сферических и несферических систем; вводится макропараметр D, характеризующий отклонение возмущенной системы от определенного состояния. Результатом данной работы является вывод о том, что в целом после введения возмущений система стабилизируется, а степень стремления системы к приобретению начальной формы зависит от характера вводимых возмущений и их магнитуды. Наблюдается волна плотности, проходящая с течением времени от центра системы к периферии. Можно заключить, что изотропное распределение Хернквиста необратимо по отношению к вводимым возмущениям его структуры.

Ключевые слова: эллиптические галактики, распределение Хернквиста, устойчивость, возмущения, моделирование N-тел.

Introduction. Elliptical galaxies are a common type of observed galaxies in the Universe. They are found mainly in clusters of galaxies, and their masses and luminosities vary greatly: from dwarf galaxies with a mass of 10^5M_0 to massive galaxies, which include about $10^{13}M_0$ and have a supermassive black hole in the center. Elliptical galaxies have a spherical or ellipsoidal shape, the preservation of which, as a rule, is not played by rotational motion, as in spiral galaxies, but by the velocity dispersion of stars.

Observations of elliptical galaxies using large ground-based and space telescopes (GMOS, VLT, Hubble, Chandra, Spitzer etc.) make it possible to obtain detailed kinematic characteristics with a spatial resolution of their central parts up to 1 pc (parsec is about 3.3 light years) for the velocities and velocity dispersion of stars [1]. At the same time, the existing problems associated with their observation indicate that the mechanisms of their formation and evolution still require more careful study [2].

Elliptical galaxies are considered as collisionless systems, which means that the interaction of stars with each other, i.e., their exchange of energy and angular momentum, can be neglected, with the exception of the central regions, where the stellar density is much higher. Such a high value implies the possibility of the existence of anisotropy of velocities, which is the main mechanism leading to the non-sphericity of galaxies of this type. These galaxies, with their characteristic flattening, can have a shape close to an oblate, elongated, or triaxial ellipsoid, not exceeding certain critical values of oblateness. The shape and dynamic stability of elliptical galaxies is an urgent problem in astrophysics.

In 1975 Bertola and Capaccioli [3] determined the rotation curve of the galaxy NGC 4697 from observations, it was found that the oblateness of this galaxy cannot be explained by its rotation within the framework of the classical theory of liquid equilibrium figures. The theory of collisionless ellipsoidal equilibrium figures was well developed in the last century to study their shape and stability [4, 5]. However, the differential equations of motion in the general case are complex in this theory and are not analytically integrable. In addition, the difficulty of an analytical study of stability lies in the fact that the distribution function of stars must be known [6], and for elliptical galaxies it is extremely difficult to construct it in the general case. Therefore, to overcome these difficulties and develop the theory of the evolution of elliptical galaxies, today the main approach in this area is to turn to numerical methods and computer modeling.

Recently, observational data on elliptical galaxies and numerical simulations have made it possible to build more and more accurate dynamic models of elliptical galaxies. It is analytically impossible to construct equilibrium distribution functions for elliptical galaxies, except for special cases. One of such special cases will be considered in this work.

This article is devoted to the study of the dynamic stability of elliptical galaxy models to external perturbations affecting the internal structure of the system.

Materials and methods. 1. Generation of initial conditions according to the Hernquist distribution function. To construct the equilibrium distribution, we used the analytical model for spherical galaxies obtained by Lars Hernquist [7]. The density distribution of the Hernquist sphere is given by

$$\rho(r) = \frac{M_t}{2\pi}\frac{a}{r}\frac{1}{(r+a)^3}, \tag{1}$$

where is the total mass of galaxy, is a scale length.

To generate coordinates corresponding to distribution (1), it is necessary to “sample” this function. The most commonly used methods are “inverse transform sampling” and “rejection sampling”. The latter, due to the fact that the highest concentration of particles of a given distribution is located in the center, is not suitable for efficient generation of coordinates. Therefore, the “inverse transform sampling” method was used, based on the use of an inverse cumulative distribution function. The cumulative distribution function for expression (1) is the mass distribution function depending on the distance to the center:

$$M(r) = M_t\frac{r^2}{(r+a)^2}. \tag{2}$$

Its inverse function is

$$r_{1,2} = \frac{a\left(M(r) \pm \sqrt{M_t M(r)}\right)}{M_t - M(r)}. \tag{3}$$

Next, projections of position vectors on the coordinate axes are generated using the formulas for converting spherical coordinates to Cartesian ones.

To generate velocities, we used the full distribution function given by [7]

$$f(E) = \frac{M_t}{8\sqrt{2}\left(\pi a v_g\right)^3}\frac{1}{\left(1-q^2\right)^{5/2}} \times \left(3\arcsin(q) + q\sqrt{1-q^2}\left(1-2q^2\right)\left(8q^4-8q^2-3\right)\right), \tag{4}$$

where

$$q = \sqrt{-\frac{a}{GM_t}E}; \quad v_g = \sqrt{\left(\frac{GM_t}{a}\right)}.$$

Here is the gravitational constant, is a specific energy.

We used the “rejection sampling” method using the maximum value of the function (4) as the envelope function. In order for the system to be gravitationally bound, we selected velocities whose values are less than the escape velocity for each particle.

2. Introducing perturbations into the Hernquist distribution function. We introduced perturbations into the structure of the density distribution of the Hernquist model corresponding to the tidal effect from another galaxy or galactic cluster. The algorithm of this perturbation is as follows. First, a direction is chosen in the form of a unit vector n along which the perturbation will act. This direction is characterized by one parameter - the polar angle, i.e. the angle between the axis of symmetry of the galaxy and the gradient of the potential. Since we are considering only axially symmetric systems, the azimuthal angle does not matter. Then the

parameter h is introduced, which characterizes the force of the tidal influence (modulus of the potential gradient). This parameter will determine the degree of deformation. As a result, the perturbation is introduced by the shift of all particles of the galaxy along the positive direction n, if the angle between the radius vector of the particle and the vector n is obtuse, and in the opposite direction, if this angle is acute (particles whose radius vector is perpendicular to n do not shift). Formally, this is expressed as

$$\vec{r}\,' = \vec{r} + \frac{h\vec{n}(\vec{n}\vec{r})}{r}, \tag{5}$$

where and are the positions of a particle in a disturbed and equilibrium systems respectively, is a modulus of the vector . Thus, the algorithm for generating the initial conditions is reduced to a certain degree of flattening of the Hernquist sphere along the Z-axis. Therefore, this flattening is done by multiplying the z-coordinates of particles by the flattening coefficient β.

3. Density profile and velocity dispersion analysis method. After generating the initial conditions, we prepared an initial snapshot for the integrator Gadget2 [8], which is a binary file with a specific structure. Next, we ran the integrator up to 6 Gyr. Gadget2 is freely available N-body simulation code using parallel computing technologies. The code is based on the calculation of gravitational forces using a hierarchical tree algorithm for self-gravitating collisionless N-body systems.

3.1. Spherical model. If the system preserves spherical symmetry, then it is sufficient to investigate only the radial dependence. In this case, to construct radial dependences for density or velocity dispersion, it is necessary to take, as the reference point not the center of mass of the system, but the point of maximum density; the difference between them is that all stars, including very distant and solitary ones, influence the position of the center of mass.

For this, the “shrinking sphere” method is used [9]. It is based on finding the center of mass in spheres that shrink logarithmically at each iteration step. The iteration continues until the limit mass in such a sphere is reached. The coordinates for the true center of mass for the whole system are calculated from the remaining number of particles in the last sphere. The use of a logarithmic scale is associated with a large concentration of particles in the central regions of the distribution.

In the case of spherical symmetry, the system parameters are measured in concentric layers (density and velocity dispersion). For example, the density of particles at a given radius is the number of particles in a layer at that radius divided by the volume of the layer. Since the concentration of particles decreases with distance from the center, it is impractical to use layers of the same thickness. For uniform statistics, the thickness of the layers also increases logarithmically from the center.

It should be noted that for the unperturbed Hernquist sphere, the density and velocity dispersion profiles for the generated particles should correspond to the profiles obtained through analytical expressions (1) and

$$\overline{v_r^2} = \frac{GM_t}{12a}\left\{\frac{12r(r+a)^3}{a^4}\ln\left(\frac{r+a}{r}\right) - \frac{r}{r+a}\left[25 + 52\frac{r}{a} + 42\left(\frac{r}{a}\right)^2 + 12\left(\frac{r}{a}\right)^3\right]\right\}. \tag{6}$$

In addition, they should not change over time (within the limits of the “digital noise”), which is the verification of the correctness of the generation of the initial conditions, the operation of the integrator code and numerical analysis tools.

3.2. Non-spherical model. In the case of introducing a perturbation in the form of flattening along any axis, spherical symmetry is violated, which means that we can no longer use the method for calculating system parameters based on spherical concentric layers, as described in Section 3.1. Then the parameters should be measured independently along the Z-axis and perpendicular to it. For this, for example, points with a logarithmic step are selected along the Z axis, an imaginary sphere with a radius equal to half the distance to the previous point is taken around them, the number of stars falling into this sphere is counted and divided by its volume (in the case of calculating the local density). At the same time, since the symmetry about the XY plane is preserved, the same procedure can be done in two directions (positive and negative Z), and then the values averaged along these two directions - this will give better statistics.

Another method for assessing the macro state of the system is the introduction of a parameter (deviation parameter D) characterizing the deviation of the state of the system from a given initial perturbed or unperturbed state. This parameter is a cumulative number obtained by summing the absolute difference between the initial and subsequent distributions in the space sampled using the tree algorithm. The first step is to divide the threedimensional space into a certain number of subvolumes and check what mass is contained in them. If this mass exceeds a certain limiting predetermined mass, then each subvolume, in turn, is divided in a similar way before the onset of the specified condition, and so on. At the end of sampling, this "grid" is saved and then remains unchanged. The discretization of the volume is visually presented in Figure 1 for different degrees of flattening of the system. The mass limit used corresponds to 2000 particles in the remaining subvolumes.

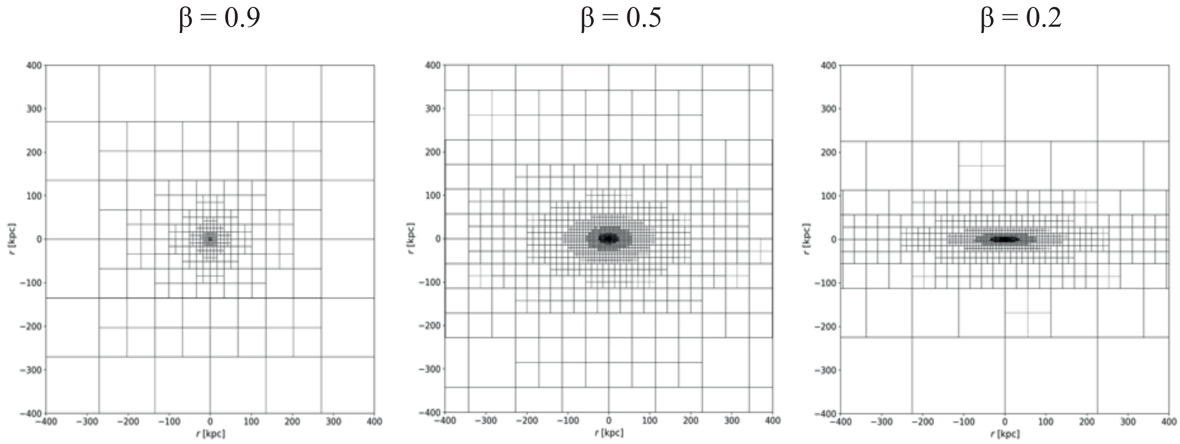

β = 0.9 β = 0.5 β = 0.2

Figure 1. Discretization of volume according to the condition that mass in each cell must be less than the one specified. Flattening coefficient β is equal to 0.9, 0.5 and 0.2 (from left to right)

After this procedure, the absolute difference of particles is calculated for the subsequent stage of evolution in each cell of the "grid". These values are summed up and normalized to the total mass of the system:

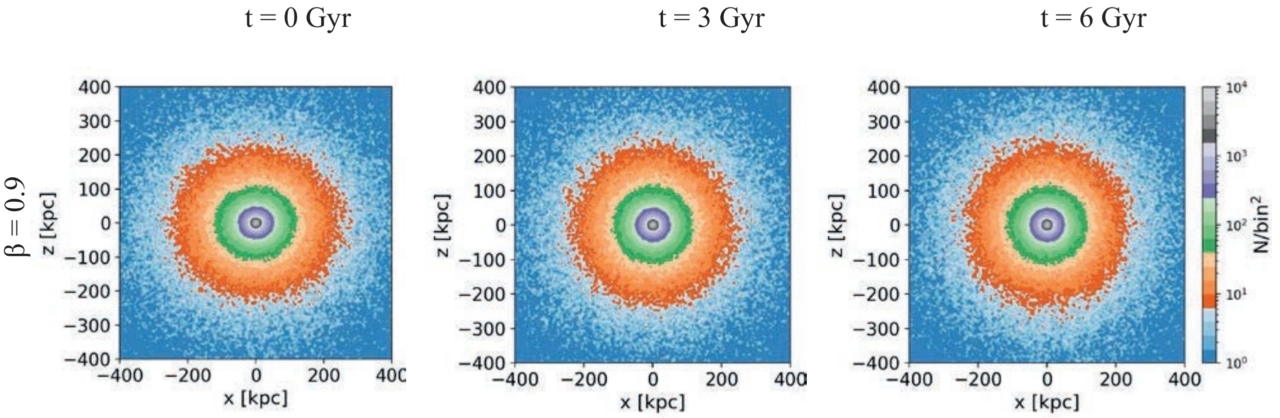
$$D = \frac{1}{M_t}\sum_{i}^{N}\left|m_i^0 - m_i^s\right|, \tag{7}$$

where is the total mass of the system, N is the number of the final subvolumes, and are masses in the i-subvolume at the initial and compared times, respectively.

Thus, we can get one number D characterizing the deviation of the system from the original at different moments of evolution. It should be noted, that this parameter D strongly depends on chosen mass limit, i.e., on the size of the final subvolumes. If the mass limit is too small, then even a stable unperturbed system generated by the Hernquist distribution will show strong deviations from its initial state during evolution.

Results and discussion. To study the stability of the Hernquist distribution, we introduce perturbations into the structure of the density distribution with different flattening coefficients β (from 0.1 to 0.9).

As we can see from the Figure 2, the system comes to an equilibrium state after some changes in the structure. In fact, it returns from the elliptical shape to an almost spherical one, then again takes on some ellipticity and does not change anymore. Thus, the system comes to an equilibrium state after a certain oscillatory phase. The color map characterizes the density of particles in bins.


t = 0 Gyr t = 3 Gyr t = 6 Gyr

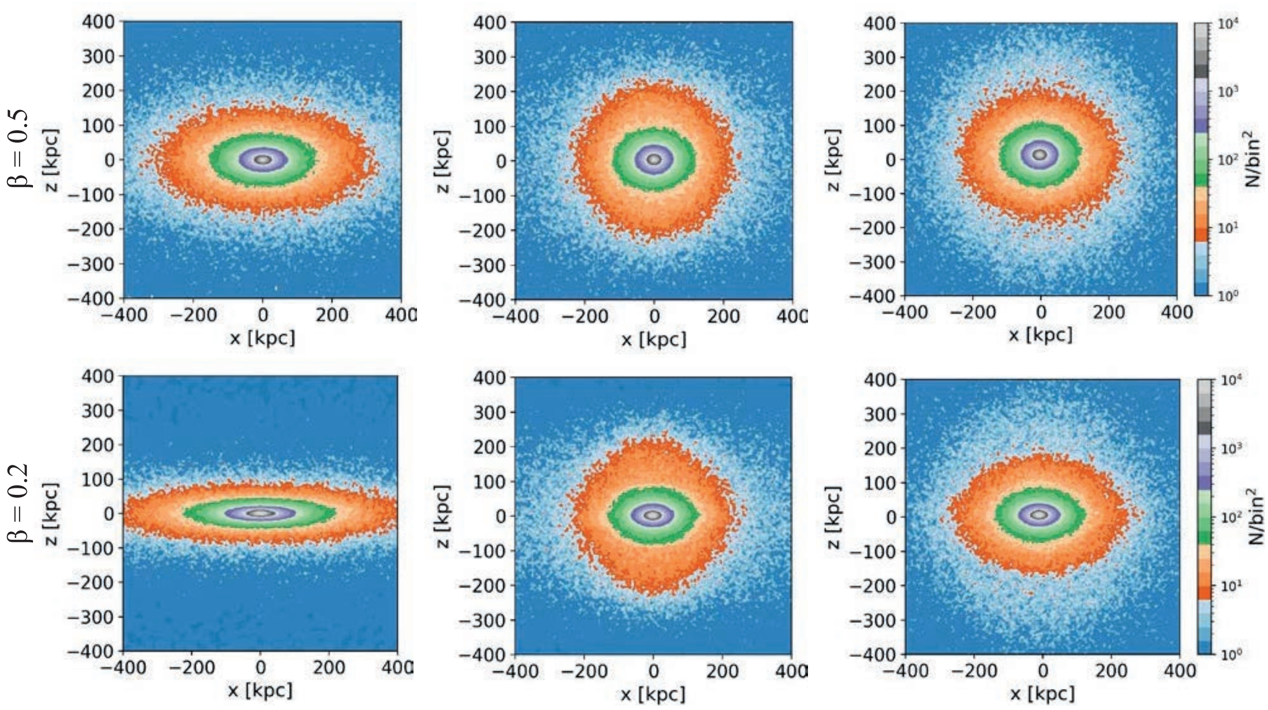


Figure 2. Evolution of the Hernquist flattened sphere (flattening coefficient β is equal to 0.9, 0.5 and 0.2 from top to bottom, respectively)

Figure 3 shows constructed density profiles by different axes at start and end times for different flattening coefficient β. The bottom plots under every figure show the relative difference compared to the analytical solution. It can be seen from them that, up to a certain point, the density profiles tend to approach the analytical distribution. In addition, especially on graphs with a strong flattening coefficient β, a density wave is visible running from the center to the periphery of the system.

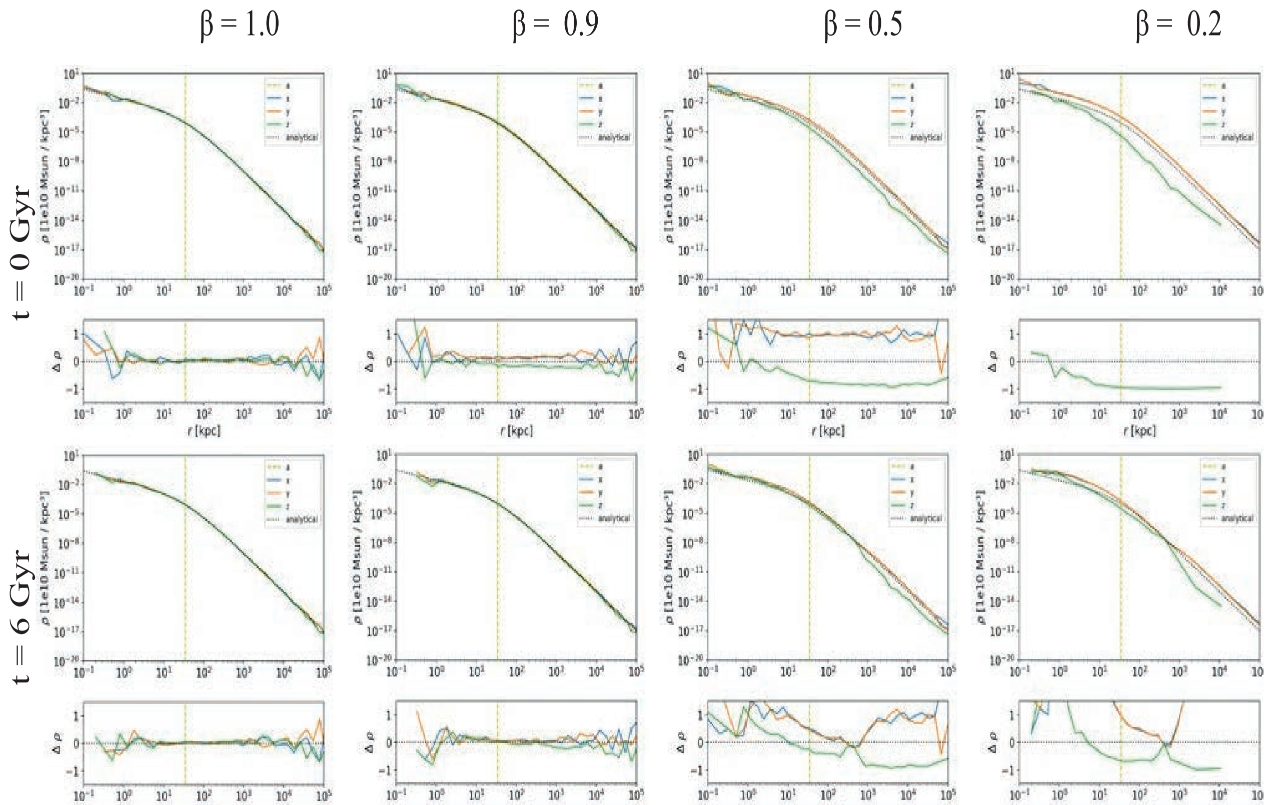


Figure 3. Density profiles of the flattened Hernquist sphere along three axes for the initial (top) and final (bottom) moments of evolution with different flattening coefficient β

We estimated the deviation of the system from its initial condition and from unperturbed Hernquist distribution using the deviation parameter D described above in section Methods.

The resulting parameters D for different flattening coefficient β is shown in Figures 4 and 5. Figure 4 presents evolution of the deviation parameter D calculated relative to the initial state of each system and corresponding flattening dependence of the parameter at the time of 6 Gyr – the moment the system almost reaches equilibrium. To establish an equilibrium state, systems with different flattening need different times: the most flattened one comes to this state the longest. Second plot on Figure 4 suggests some elasticity of the system depending on its initial flattening.

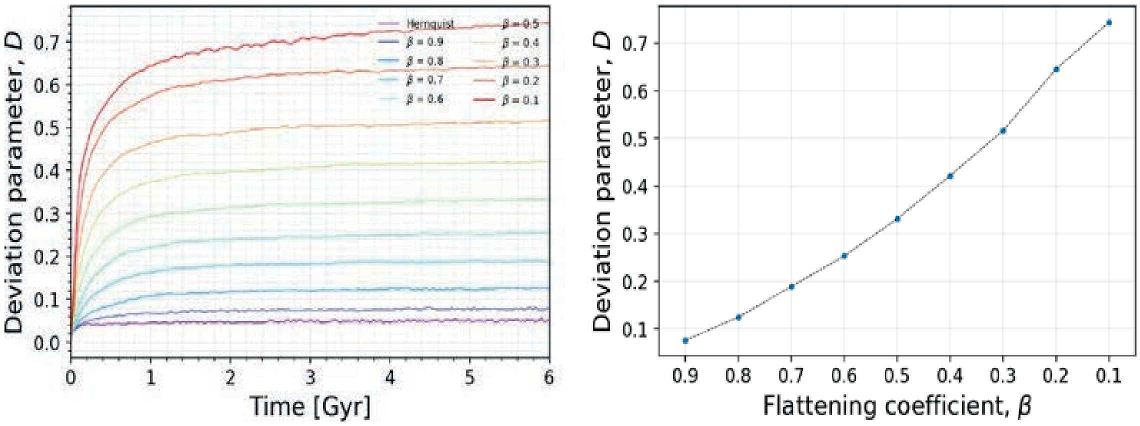


Figure 4. Evolution of parameters D of the system deviation in relation to its initial state (left) and dependence of the parameter on the flattening of the system (right)

Figure 5 shows similar data but with the deviation parameter D calculated relative to the unperturbed Hernquist distribution. We can see that even a small perturbation introduced into the system does not allow it to return to its initial state. It follows from this that the Hernquist distribution is irreversible with respect to such perturbations.

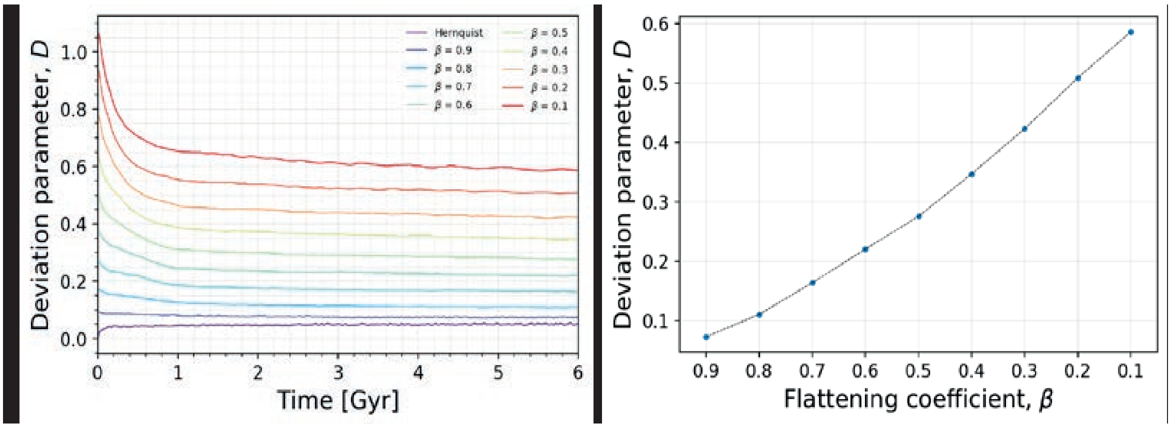


Figure 5. Evolution of parameters D of the system deviation in relation to the unperturbed Hernquist distribution (left) and dependence of the parameter on the flattening of the system (right)

As we can see, the isotropic Hernquist distribution is not stable with respect to flattening perturbations whichever their magnitude is. With that we note that certain degree of stiffness in the sense that the perturbation magnitude and the resulting deformation are related in a non-linear fasion.

Conclusion. We have considered variations of the Hernquist distribution with introduced perturbances and analyzed their stability. We saw that depending on the degree of perturbations, the system passes through an oscillatory phase. After this, the system comes to some stable state, but does not return to its original state, not to mention the isotropic Hernquist distribution. From this we can conclude that the Hernquist distribution is irreversible with respect to perturbations of its structure. It should be noted that the parameter used to assess the macro state of the system does not fix the oscillating phase of the system.

For further more detailed analysis, it is necessary to consider the orbits of individual stars at different distances from the center of the system in order to determine the degree of their change in connection with the introduced perturbations; to carry out their nonlinear analysis in order to understand the processes of parametric resonance and destruction of periodic orbits, as well as their stochasticity. In addition, to construct equilibrium elliptic systems, it is planned to use the GalIC code [10], which uses the current distribution of velocities to set the velocity structure at each subsequent iteration, and, in particular, deformed Hernquist sphere, generated with its help, will be almost perfectly equilibrium.

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МАЗМҰНЫ

БИОТЕХНОЛОГИЯ

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