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NUMERICAL SIMULATION OF THE GALAXIES OUTER SPIRAL STRUCTURE: THE INFLUENCE OF THE DARK HALO NON-AXISYMMETRY ON THE GASEOUS DISK SHAPE

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Abstract. A detailed analysis of the results of numerical simulation of the outer spiral structure in a gaseous galactic disk caused by the presence of non-axisymmetry in the distribution of matter in a dark halo have been fulfilled. The result obtained in our previous work [8] that the non-axisymmetry of the gaseous disk is less than the non-axisymmetry in the dark mass distribution for disks with a spiral structure extending far beyond the optical radius, have been confirmed. Also, the result has been generalized for the dark halo model, which is spherical within the optical radius and non-axisymmetric beyond it.

Key words: hydrodynamics, outer spiral structure, numerical simulation, dark halo, non-axisymmetry.

Introduction

Astronomers have been recently observing galaxies with atypically extended spiral arms. Explanation of the formation mechanism of such a global spiral pattern far beyond the optical radius, R_{out}, represents a serious problem. Such a spiral pattern is revealed by the distribution of the gas component HI and/or in the ultraviolet. The best-known object with outer spiral arms is the galaxy NGC 1512. According to the GALEX data, the length of the outer arms for NGC 1512 is several times greater than its optical radius.

The similar pattern to the one described above is also observed in the galaxies NGC 289, NGC 4151, NGC 4736, NGC 5055, NGC 6744, NGC 5236, NGC 7793, etc. [2; 7; 13]. The outer arms for NGC 5055 are clearly visible on its HI-map [7] (see right frame in figure 1). Similar observational data had been presented for NGC 6946 in Ref. [8].

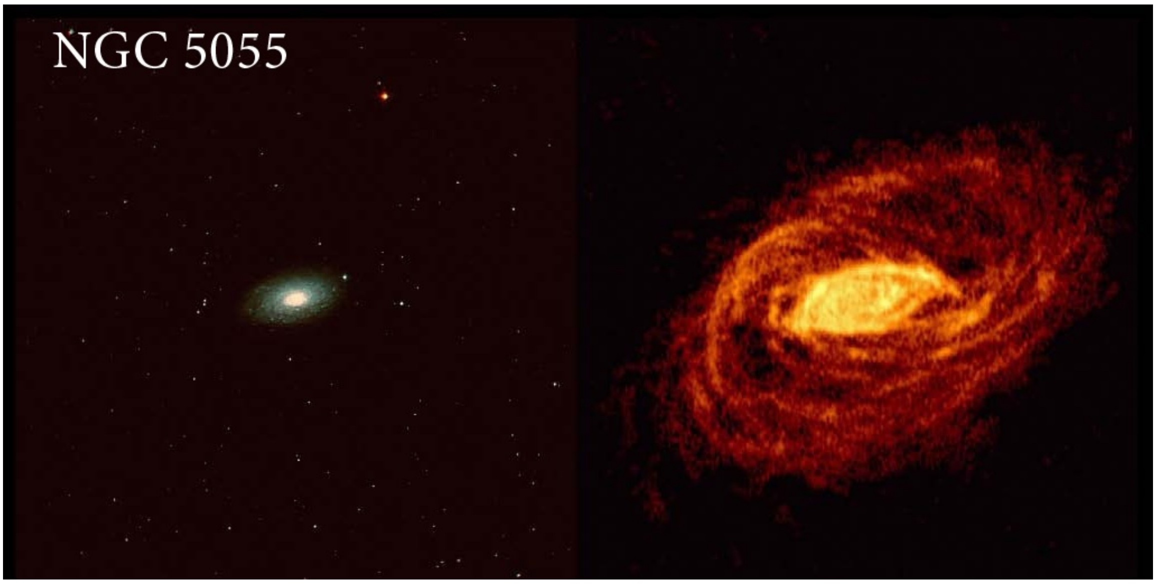

Fig. 1. The left frame shows a color composite optical image of the Digitized Sky Survey of the NGC 5055 galaxy. The right frame shows a deep HI map of NGC 5055 at the same scale as the optical image [7]

It should be noted that absence of such extended outer spirals in the gaseous disk of the galaxy cannot be explained by the presence of a spiral stellar density wave or a bar. The gravitational instability of the gas cannot significantly affect the formation of a global spiral pattern outside the optical radius, since the gas density there is rather low. On the contrary, if we assume that there is enough gas at the periphery for the development of gravitational instability, then this instability should lead to the destruction of the spiral pattern formed by a non-axisymmetric halo. In Ref. [3] had been shown that the effect of the non-axisymmetry of a dark halo with a large gravitating mass can serve as an effective mechanism for generating extended outer spiral structures.

Currently the main hypothesis explaining the plateau in the rotation curves of galaxies at distances $r > R_{out}$ is the existence of a non-spherical triaxial ellipsoidal halo of dark matter, inside which a galaxy is formed at the stage of the cosmological expansion of the Universe. During the evolution process, interaction with baryonic matter can actively influence the shape of such halos and change their density profiles [12]. Modern results of observations of the Galaxy, as well as objects close to us ($z \ll 1$) confirm that the mass distribution in the dark halo keeps its triaxial character, possibly with the exception of the central regions ($r \ll R_{out}$). The latter we accounted for in the models developed in Ref. [8], where various shapes of the non-axisymmetry dependence on the galaxy radius were considered.

Studying the reasons of this phenomenon we have considered various hypotheses of external spiral structures formation. For example, we examined the propagation in the outer gas disk of large-scale spiral waves that arise inside the optical disk as it was described in Refs. [10; 11]. In the paper [14] it was assumed that rapid cooling of the gas, leading to the formation of giant molecular clouds, may be responsible for the multi-armed spirals formation.

In current article we suppose that the main hypothesis of outer spiral structures formation is the influence of the dynamic interaction of a non-axisymmetric halo and a gaseous galactic disk [3; 4; 8]. The hypothesis of a non-axisymmetric halo as an effective mechanism for generating a spiral density wave had been already considered in Ref. [5]. The above papers demonstrate the effectiveness of the mechanism proposed in Ref. [5] for the formation of outer spiral arms outside the optical radius of the galaxy. In Ref. [8] we analyzed the results which evidence in favor the influence of non-axisymmetric dark halo "shape", on the morphology of the generated spiral pattern in the gaseous galactic disk model. In developed numerical models the "shape", of the dark halo is determined by various functional dependences of the non-axisymmetry parameter, ε, on the disk radius, r. In current article we adapt the models constructed in Ref. [8] to analyze the impact of the halo non-axisymmetry value on the final asymmetry of the gaseous disk.

1. Mathematical and numerical model

In our model we use the complete system of hydrodynamic equations for an ideal gas. The gas is in the external potential, which is described in the Refs. [4; 8]. To solve the system of ideal gas dynamics equations a finite-volume MUSCL-type numerical scheme [16] was applied as it was described the Refs. [4; 8]. The fluxes of physical quantities through the boundaries of the computational cells were calculated using the HLLC modified method to allow calculation at the boundary with vacuum. Primitive variables [15] were used to reconstruct the distribution of gas dynamic parameters inside the computational cells. Self-gravity was accounted for using the TreeCode method [1]. The mathematical model, its parameters used in the numerical simulation, as well as the form of the analyzed functions, $\varepsilon(r)$, had been described in detail in Ref. [8]. The parameters of our basic numerical model had been considered in detail in Ref. [4].

The parameters of our basic model correspond to the physical parameters of the Galaxy given in Ref. [9]. The surface density distribution function sets a sufficient amount of gas at the disk periphery beyond R_{out}, and cut off distance equals to three optical radii, $R_{out} = 12$ kpc.

In this work the main peculiarity is in the value of the non-axisymmetry parameter of the dark halo, which is given by the quasi-isothermal model [8]. According to Ref. [8] this parameter has the strongest effect on the morphology of the generated external spiral pattern.

Numerical simulations have been executed on a cylindrical grid: $N_r = 500$ cells in radius, $N_\varphi = 180$ cells in azimuth. The size of the computational domain, $R_{\max}$, equals to three optical radii, R_{out}, which corresponds to $R_{\max} = 36$ kpc (radius unit is 1 kpc, velocity unit is 40 km/s). To eliminate the influence of the computational grid size on the results of simulations some calculations were performed again on larger and finer grids.

A comparative analysis of the initial non-axisymmetry of the dark halo and the final non-axisymmetry of the disk has been fulfilled in current article. It should be noted that the halo non-axisymmetry parameter in our models can be calculated as follows: $\varepsilon = 1 - a_x/b_y$, where a_x and b_y are the scales of the halo along the axes OX and OY, respectively, given in its quasi-isothermal model. Here we also have introduced a parameter characterizing the non-axisymmetry of a gaseous disk. We have evaluated the non-axisymmetry of a disk at the later stages of its evolution by comparing its size along the primary (r_x) and secondary (r_y) axes. The non-axisymmetry of the disk is estimated as follows: $\varepsilon = 1 - r_x/r_y$ by analogy with the halo non-axisymmetry parameter. But we haven't set it initially, it's value is determined during the calculation as a result of dynamic modeling. We also have supposed that the density distribution in the disk is symmetrical at the initial time instant.

To perform post-processing of files containing the results of hydrodynamic modeling a Python script was written. The main task of this script is calculation of the average values of the surface density along the primary and secondary axes of the gaseous disk for several periods of its rotation. The data obtained after post-processing was recorded into a text file and visualized. The density values along different axes of the disk allowed to estimate its non-axisymmetry using the expression above.

2. Results and discussion

Previously, in Refs. [3; 4] the obtained results of hydrodynamic simulation confirmed that presence of non-axisymmetry in the distribution of halo matter is an effective mechanism for the formation of external spiral structures. In Ref. [8] we considered the influence of various numerical model parameters on the morphology of spiral structures generated by a non-axisymmetric dark halo. Here we continue the analysis of the influence of the “shape”, of the dark galactic halo on the morphology of the spiral pattern formed on the periphery of the gaseous disk outside the optical radius. In particular, we have estimated how the non-axisymmetry of the halo affects the symmetry of a gaseous disk during its evolution in the external gravitational potential.

In Ref. [8] it had been shown that in absence of non-axisymmetry in the dark matter distribution on the disk periphery an extended and long-lived spiral structure has not form. In current work we study the only case of function $\varepsilon(r)$ when halo is symmetric at the center and non-axisymmetric outside the optical radius (1):

$$\varepsilon(r) = A - B \tanh((r - R_{out})/L_e) \tanh(-R_{out}/L_e)\,, \qquad (1)$$

where R_{out} is the optical radius of the disk, $A = (\varepsilon_{\min} + \varepsilon_{\max})/2$, $B = (\varepsilon_{\max} - \varepsilon_{\min})/2$. Parameters $\varepsilon_{\min}$ and $\varepsilon_{\max}$ determine the minimum and maximum values of the non-axisymmetry parameter of the halo, L_e – the width of the transition zone between two limiting values of the non-axisymmetry parameter.

In current work we carried out a series of experiments with two different values of L_e parameter ($L_e = 0.2$ and $L_e = 0.05$). At the same time, we varied the maximum value of the non-axisymmetry parameter over a wide range of values: $\varepsilon_{\max} = 0.05 \div 0.4$, that corresponds to 5% $\div$ 40%. As shown earlier in Ref. [8], the value of parameter L_e affects the morphology of the spiral arms only in the central region of the disk and does not significantly influence the morphology of considering outer spirals. We can observe this when comparing figures 2 and 3, which show the distributions of the logarithm of the disk surface density function at time instant $t = 120$ corresponding to 4 disk rotation periods. In each of the figures successively is shown the density distribution obtained for one of $\varepsilon_{\max}$ values from the above range. As shown earlier, for the transition parameter $L_e = 0.05$, we observe the formation of small-scale structures in the central region (see figure 3). Previously, we have shown that parameter $\varepsilon_{\max}$ has the most significant effect on the morphology of the outer spiral structure of the galaxy.

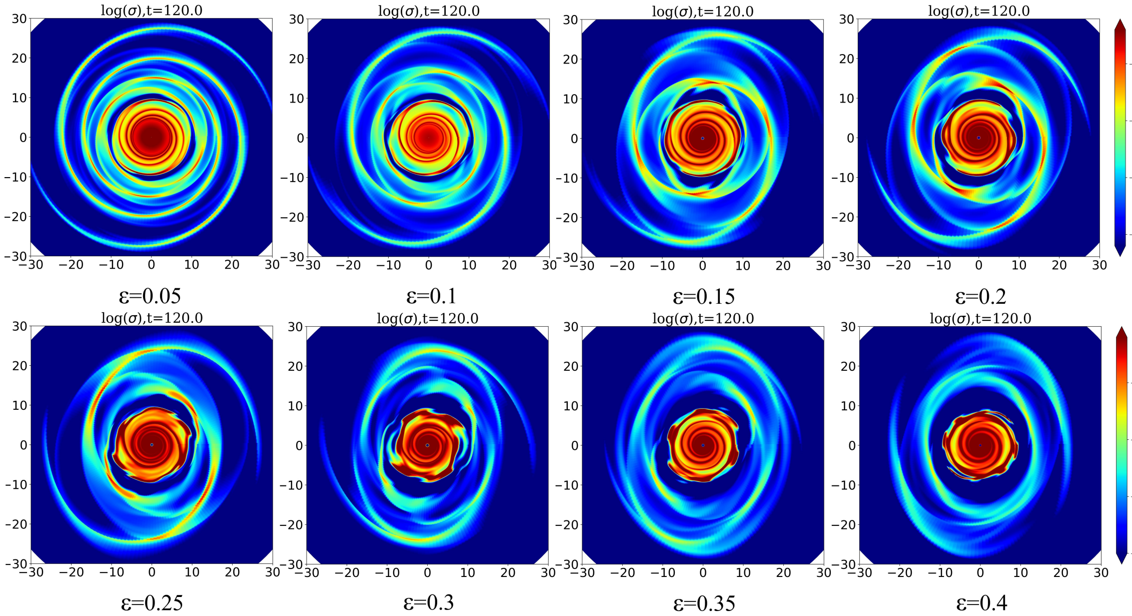

Fig. 2. The distribution of the logarithm of the gas surface density function, $\sigma(r, \varphi)$, at time instant $t = 120$ for various values of $\varepsilon_{\max}$ for $L_e = 0.2$

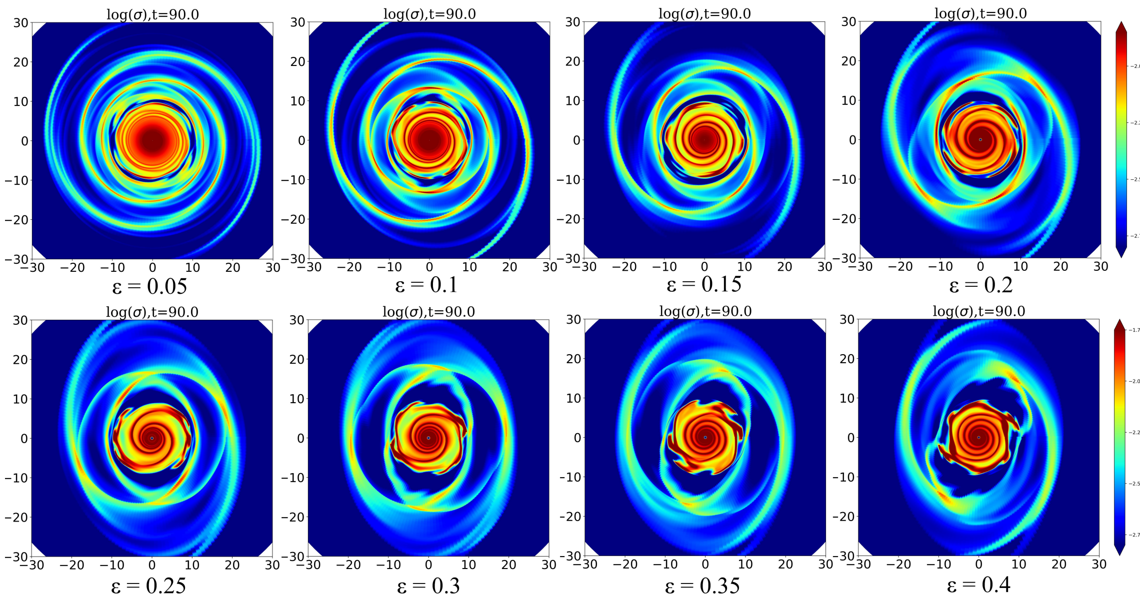

Fig. 3. The distribution of the logarithm of the gas surface density function, $\sigma(r, \varphi)$, at time $t = 120$ for different values of $\varepsilon_{\max}$ for $L_e = 0.05$

Results presented in this article allows to confirm the relationship between the non-axisymmetry of the disk and spheroidal components of a galaxy described in Ref. [4] and expand it to the systems with external spirals. Applying the script for post-processing of files containing the newly obtained results, we got the distributions of the surface density of the disk along the primary and secondary axes. Figure 4 shows the examples of such distributions for different values of halo non-axisymmetry parameters, the left column corresponds to the value $L_e = 0.2$, and the right column shows the distributions for $L_e = 0.05$. The distributions of the average values of the surface density along the primary and secondary axes are shown by different line types.

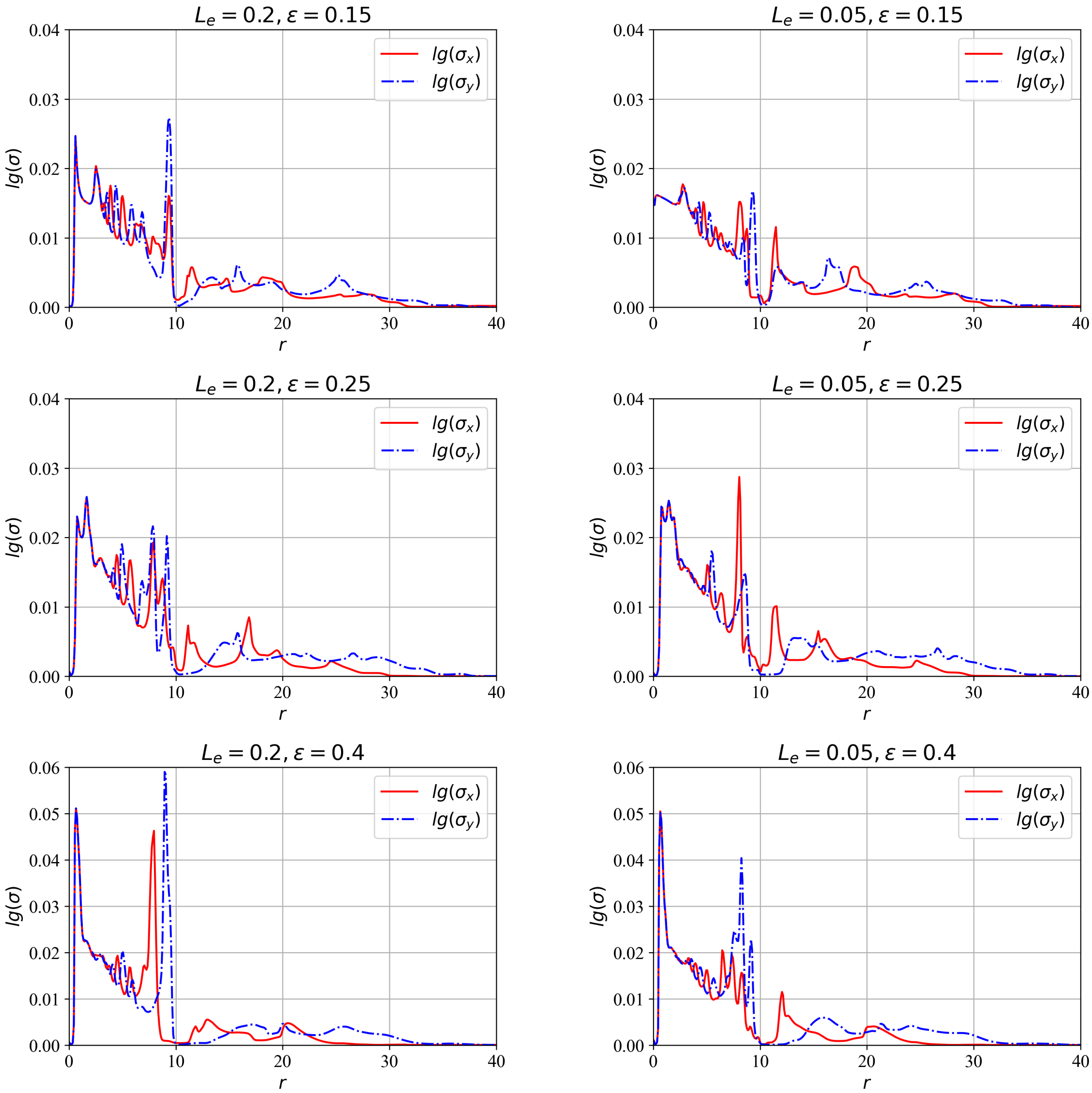

Fig. 4. The distribution of the average value of the logarithm of the gas surface density function $\sigma(r, \varphi = 0)$ (solid line) and $\sigma(r, \varphi = 90)$ (dashed line). The right column shows the distributions for $L_e = 0.05$, the left column shows the distributions for $L_e = 0.2$

From figure 4 we may determine the radius value at which the gas density decreases almost to zero along each of the axes. We have assumed that this distance defines the boundary of the gaseous disk. Figure 5 shows the dependence of the halo non-axisymmetry parameter which is set as an input parameter of the external potential at the beginning of the simulation, on the non-axisymmetry of the disk computed as a result of evolution. We have averaged the values over the three rotation periods from the 4^{th} to the 6^{th} periods. We have considered only the dynamics which does not include the early stages of disk evolution, when the spiral structure has not yet formed. It is clearly seen that the elongation of the disk tends to increase with the rise of the parameter $\varepsilon_{\max}$, but it does not grow as fast as the non-axisymmetry of the halo.

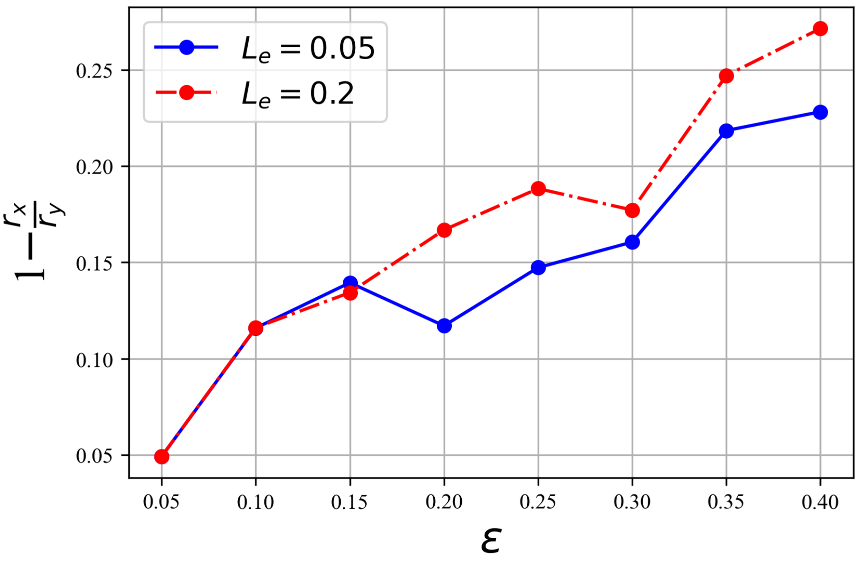

Fig. 5. The dependence of the halo non-axisymmetry parameter ε on the gas disk non-axisymmetry parameter $\varepsilon = 1 - r_x/r_y$. The solid line corresponds to $L_e = 0.05$, the dotted line — $L_e = 0.2$

3. Conclusions

Two series of gas dynamic calculations have been carried out for different values of the width of the transition zone of the non-axisymmetry parameter from minimum to maximum value. The results of numerical simulation have been analyzed for a wide range of values of the non-axisymmetry parameter of the dark halo. Simulation has shown that for any of the given values of the parameter $\varepsilon_{\max}$, an extended and long-lived outer spiral structure is generated. Calculations also confirmed that the value of the $\varepsilon_{\max}$ parameter has a significant effect on the morphology of the external spiral structure formed during the evolution, as it was shown in Ref. [8].

We generalized results according to which the non-axisymmetry of the disk is much less than the non-axisymmetry of the dark halo, described earlier in Ref. [3], to a wider range of values of the halo non-axisymmetry parameter, and on a model where this parameter depends on the radius of the disk. To achieve this the script which allows pre-processing of the simulation results recorded in the state files of the hydrodynamic system was written. After such pre-processing for each calculation we computed the value that indicates the non-axisymmetry of the gaseous disk for the given system parameters at the later stages of disk evolution, when the spiral has already formed and stable.

The comparison of the disk and the halo non-axisymmetry for considered values of parameter $\varepsilon_{\max}$ demonstrated that starting from 15% value of the halo non-axisymmetry, the non-axisymmetry of the disk becomes less pronounced. Also, we observe the increase in the disk non-axisymmetry with an increase of the parameter $\varepsilon_{\max}$, but this growth slows down significantly. It should be noted that for the values of parameter $\varepsilon_{\max} < 15\%$, we obtain equality and even an excess of the non-axisymmetry value of the disk relatively to the value of $\varepsilon_{\max}$. This result is new, since earlier in Ref. [3] the values of $\varepsilon_{\max}$ exceeding only 20% have been considered, namely $\varepsilon = 0.2$ and $\varepsilon = 0.3$. This result needs to be clarified in following research. The trend we got is in consistency with the observational data: since we do not register objects that are strongly elongated along the axes.

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ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ВНЕШНЕЙ СПИРАЛЬНОЙ СТРУКТУРЫ ГАЛАКТИК: ВЛИЯНИЕ НЕОСЕСИММЕТРИИ ТЕМНОГО ГАЛО НА ФОРМУ ГАЗОВОГО ДИСКА

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Аннотация. В представленной работе проведен анализ двух серий численных гидродинамических экспериментов, моделирующих внешнюю спиральную структуру за пределами оптического радиуса галактики. Такие спиральные структуры мы наблюдаем в некоторых галактиках, в основном в ультрафиолетовом диапазоне. Каждая серия расчетов соответствует фиксированному значению параметра L_e, определяющего ширину переходной зоны между минимальным и максимальным значением параметра неосесимметричности темного гало ε. Ранее было показано, что величина ε влияет на морфологию формирующейся спиральной структуры только в центральной области диска. Сам же параметр ε варьировался в широких пределах. Основной целью работы было обобщение результата, подтверждающего малую неосесимметричность в распределении вещества в газовом диске относительно распределения вещества в темном гало. Мы распространили этот результат на модель гало, в которой неосесимметрия зависит от его радиуса (сфероизация в центральной области), а также проанализировали более широкий диапазон значений параметра ε. Для обобщающего результата мы определили параметр неосесимметричности для газового диска следующим образом: $\varepsilon = 1 - r_x/r_y$, размеры диска по главной (r_x) и побочной (r_y) осям, по аналогии с параметром неосесимметрии гало. Мы определяем r_x и r_y из распределений значений поверхностной плотности вдоль главной и побочной осей диска, усредненных за три периода вращения диска. Результаты моделирования и нашей постобработки показывают, что при любых, кроме самых маленьких из рассмотренных нами значениях параметра ε, неосесимметричность диска менее выражена, чем неосесимметрия темного гало. Это соответствует данным наблюдений.

Ключевые слова: гидродинамика, внешняя спиральная структура, численное моделирование, темное гало, неосесимметрия.