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Analysis of data on lopsided galaxies and theories of their formation

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Abstract. Ground-based and space observations show that the nuclei of many disk-shaped galaxies are significantly offset from their geometric center. This can lead to the excitation of the lopsided mode $m = 1$. To determine the dependence of this effect on the geometry of the system, in this work we have compared a non-stationary disk model with respect to the gravitational instabilities of the lopsided mode $N = 3$; $m = 1$ perturbation. In this work we have also compiled a summary catalog of lopsided disk-shaped galaxies and conducted a statistical analysis of their physical parameters.

Keywords: galaxies: evolution, formation, kinematics and dynamics, structure

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1 Introduction

Lopsided structures in galaxies were first noticed in the work (Baldwin et al. 1980) based on the distribution of H I in 20 galaxies. It has been shown that the fraction of lopsided structures in spiral galaxies can reach 30 % or more (Jog & Combes 2009). Obviously, lopsidedness is associated with the nonstationary evolution of the galaxy. The high proportion of galaxies that demonstrate lopsidedness indicates that it is quite stable over a long period of time (Bournaud et al. 2005). Many authors have analysed images of galaxies not only in the optical but also in the near-infrared range and characterised the asymmetry using Fourier analysis. Various physical mechanisms have also been identified that cause the isophotes of the density center to shift from the geometric center in a disk galaxy. For example, the response of the disk to the halo arising from tidal interactions (Jog 1997) or mergers of satellite galaxies (Zaritsky & Rix 1997) or tidal collisions (Mapelli et al. 2008) and asymmetric gas accretion (Bournaud et al. 2005) can lead to the excitation of the lopsided mode $m = 1$.

Until the 2000s, the formation of large-scale galaxy structures was mainly studied within the framework of equilibrium models (Kalnajs 1972), which are unable to explain the observational data regarding the nonlinear nonstationary stage of the evolution of self-gravitating systems. On the other hand, foreign authors have studied the problems of the origin of large-scale structures using numerical experiments (Łokas 2021), setting different degrees of non-equilibrium at the initial moment, which led to in phenomena reproducing the observed structures in real astrophysical systems. However, in numerical experiments, it is impossible to clearly determine the physical mechanism leading to the new observed state and to see possible nonlinear phenomena, resonance processes and the nature of gravitational instabilities that occurred during the experiment. The shortcomings of the above models were first taken into account in the analytical models of the authors (Nuritdinov et al. 2008), where nonlinear nonstationary pulsating models with rotation were built on the base of equilibrium models, describing the initial stages of the formation of self-gravitating systems.

2 Calculation results

We have created a catalog of 2125 lopsided disk galaxies, of which 89 % are spiral galaxies (S) and 11 % are lenticular galaxies (S0). Our main focus was to study the statistical correlation between the physical properties of the catalog. For example, we found that the correlation coefficient between the velocity dispersions of stars in

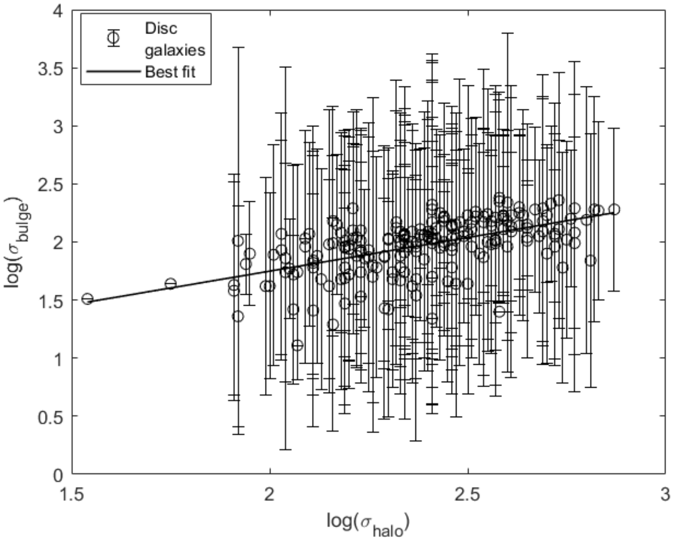

Fig. 1. Dependence of $\sigma_{\rm halo}$ on $\sigma_{\rm bulge}$ for disk galaxies.

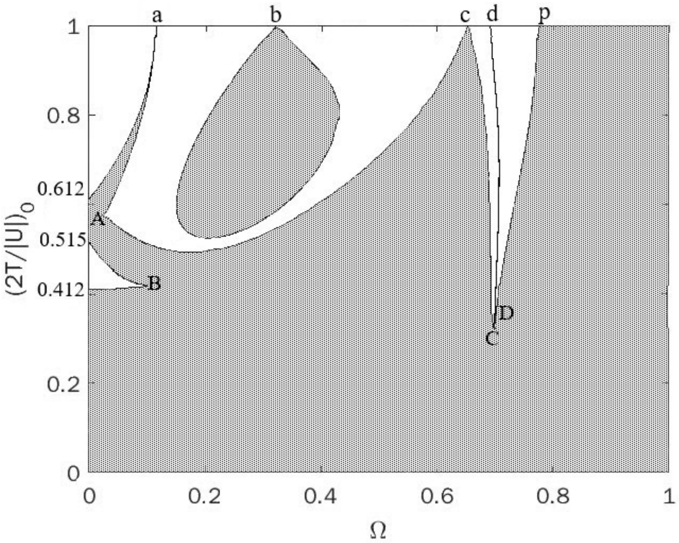

Fig. 2. Dependence of the initial virial ratio on the degree of rotation for different values of the superposition parameter $\nu = 0.75$. Here $\mathrm{A}\,(0.028; 0.576), \mathrm{B}\,(0.101; 0.421), \mathrm{C}\,(0.699; 0.331), \mathrm{D}\,(0.701; 0.348), \mathrm{a} = 0.115, \mathrm{b} = 0.320, \mathrm{c} = 0.651, \mathrm{d} = 0.693, \mathrm{p} = 0.775$.

the bulge and halo is 0.6, and the corresponding relationship is as follows (Fig. 1):

$$\log\sigma_{\mathrm{bulge}} = (0.592 \pm 0.143) + (0.579 \pm 0.060) \cdot \log\sigma_{\mathrm{halo}}\,. \tag{1}$$

Analysis of the results of the numerical calculation of the nonstationary dispersion equation for the superposition parameter $\nu = 0.75$ shows that at $\Omega = 0$ in the range of initial virial ratio values $0 \leq (2\ \mathrm{T}/|\mathrm{U}|)0 \leq 0.412$ the instability of the mode $(3;1)$ is aperiodic, while in the range $0.515 \leq (2\ \mathrm{T}/|\mathrm{U}|)0 \leq 0.612$ it is oscillatory (Fig. 2). When our nonstationary anisotropic disk model starts to rotate, only oscillatory instability is observed. In the range of rotation parameter values $0 < \Omega < 0.101$ within the instability region, we observe a peninsula of stability. Interestingly, in the stable region within the range $0.15079 \leq \Omega \leq 0.43096$ of the rotation parameter values, a beautiful island of instability was formed. At the rotation parameter values $\Omega = 0.115, 0.320, 0.651, 0.693$ and 0.775, according to our calculations, the oscillation amplitude is $\lambda \approx 0$, which corresponds to the instability of the equilibrium state.

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