10.1515/astro-2017-0210

Baltic Astronomy, vol. 24, 119–125, 2015

GALACTIC SPIRAL PATTERN BEYOND THE OPTICAL SIZE INDUCED BY THE TRIAXIAL DARK HALO

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Received: 2015 March 25; accepted: 2015 April 20

Abstract. We suggest a possible mechanism for the formation of non-tidal gaseous structures in galactic outskirts. According to recent observations, extended spiral structures are detected beyond the optical radii $R_{\rm opt}$ in numerous disk galaxies. Such features can be clearly seen in deep HI and UV images (e.g., NGC 3198, NGC 3359, NGC 2841, NGC 3198). We argue, based on our gas-dynamical simulations, that such outer spirals could form as a result of the interaction of the galactic disk with the triaxial host dark matter halo.

Key words: galaxies: kinematics and dynamics – galaxies: spiral – galaxies: structure

1. INTRODUCTION

Recently, a growing number of disk galaxies have been found to exhibit the presence of a very large spiral pattern beyond the optical size. Such phenomena can be observed in deep HI observations, UV, and even in Hα. The central question is how such structures may have formed. One of the most striking examples is NGC 1512. Both GALEX data and HI reveal very long spirals extending out to galactocentric distances of 70–80 kpc, whereas the optical size of the galaxy is much smaller, about 7 kpc (Koribalski & López-Sánchez 2009) (see Fig. 1). A similar picture is observed in NGC 2915, NGC 5055, NGC 6744, NGC 6946, NGC 5236, and NGC 7793 (Bertin & Amorisco 2010; Bigiel et al. 2010; Boomsma et al. 2008; Radburn-Smith et al. 2012; Thilker et al. 2007).

Recent observations confirm that recent star formation has taken place far beyond the optical size of non-interacting disk galaxies. Such processes are detected not only in UV but also in Hα emission. Ongoing star formation on $1-3$ kpc scales requires cooling fragmentation of the gaseous matter. At the same time, deep HI images prove the existence of very large gaseous disks containing prominent spiral structures. However, the gas density there is not high enough to support gravitational instability on large scales up to ~ 10 kpc. Whereas the galactic bar, stellar

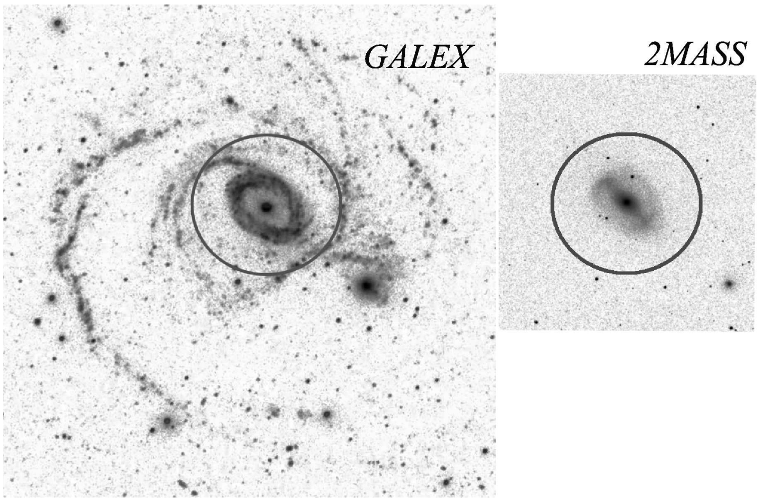

Fig. 1. UV (left) and NIR (right) images of NGC 1512. The black circle shows the optical size $R_{\rm opt}$ of the galaxy.

bulge, and spirals in the stellar component have a strong effect on the dynamics of matter in the inner part of the galaxy, they cannot determine the evolution of the outer galactic region. Hence, various types of external interactions can play a crucial part in the formation of the structure in galactic outskirts.

The gas in the outskirts appears not to feel the spatial features of the distribution of baryonic matter within the optical radius containing the host stellar disk. The flat rotation curve is a manifestation of the massive dark matter (DM) component around the galaxy. It is now assumed that DM haloes tend to be triaxial (Allgood et al. 2006). Galaxy mergers and the baryon evolution change both the shape and profile of the DM distribution (Di Cintio et al. 2014). Nevertheless, recent observations of the dynamics of nearby galaxies show that DM shape is usually triaxial, except possibly in the central region ($r \ll R_{\rm opt}$) where halo tends to be more spherical (Abadi et al. 2010).

In this paper we analyze the possibility of the formation of prominent spiral structure in the gaseous disk in galactic outskirts due to interactions with the triaxial (or non-axisymmetric in the disk plane) dark matter halo. Previously, the non-axisymmetric DM halo was assumed to be a possible driver of spiral pattern within the galactic disks (Khoperskov et al. 2012, 2013). Moreover, the spiral pattern in the dwarf galaxy NGC 2976 was also explained by the non-axisymmetric dark matter distribution (Valenzuela et al. 2014). The paper has the following layout: Section 2 describes the model and numerical method, Section 3 reports the main results, and the last section presents the concluding remarks.

2. GALACTIC DISK MODEL

Our hydrodynamic simulations are based on the TVD MUSCL (Total Variation Diminishing Multi Upstream Scheme for Conservation Laws) scheme for gas dynamics a general description of which can be found in Khoperskov et al. (2014). We performed numerical simulations on the polar mesh grid with $(N_r; N_\varphi) =$

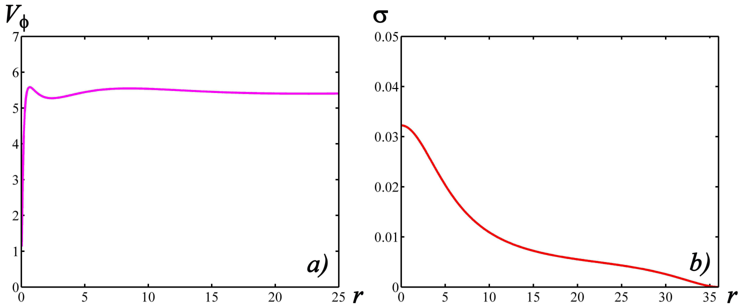

Fig. 2. (a) Model rotation curve. (b) Initial surface density distribution $\sigma(r)$.

(1500; 360). The computational domain size is $R_{\rm max} = 3R_{\rm opt} = 36$ kpc and the units used are 1 kpc for distance and 40 km s^{-1} for velocity.

The model is based on the complete system of the hydrodynamics including radiation cooling of the gas. The simulations started from the equilibrium gaseous disk settling into the galaxy potential. We assume that the total gravitational potential $\Psi_{\rm ext}$ consists of

$$\Psi_{\rm ext} = \Psi_{\rm halo} + \Psi_{\rm bulge} + \Psi_{\rm disk}, \tag{1}$$

where $\Psi_{\rm halo}$, $\Psi_{\rm bulge}$, and $\Psi_{\rm disk}$ are the potentials of the DM halo, stellar bulge, and stellar disk, respectively. For DM halo we adopted the form of an isothermal sphere, providing a flat rotation curve at the disk periphery (see Fig. 2). Numerous theoretical and observational data suggest that the DM halo has generally a triaxial shape (Allgood et al. 2006). We therefore adopt the following approximation for the DM potential:

$$\Psi_{\rm halo}(x, y, z) = 4\pi G \varrho_{\rm h0} a^2 \cdot \left\{ \ln(\xi) + \frac{\mathrm{arctg}(\xi)}{\xi} + \frac{1}{2} \ln \frac{1+\xi^2}{\xi^2} \right\}, \tag{2}$$

where

$$\xi = \sqrt{\frac{x^2}{a_x^2} + \frac{y^2}{a_y^2} + \frac{z^2}{a_z^2}}$$

is a dimensionless radius, and a_x, a_y, a_z are the spatial scales of the potential distribution along the respective axes. The bulge produces a velocity peak in the central region. We computed the potential of the stellar disk using the Bessel functions (see Binney & Tremaine 1987).

We took into account radiative cooling and heating in accordance with Hollenbach & McKee (1989). We further assumed that the gas metallicity at galactic outskirts is one order of magnitude lower than the solar value. We adopted the basic parameters of the potential from the Milky Way model designed by Khoperskov & Tyurina (2003).

3. CALCULATIONS AND RESULTS

Our gas dynamic simulations show that, over a wide range of model parameters, a long-lived two-arm spiral pattern forms at the galactic outskirts $R > R_{\rm opt}$ due to the interaction with the non-axisymmetric dark-matter halo.

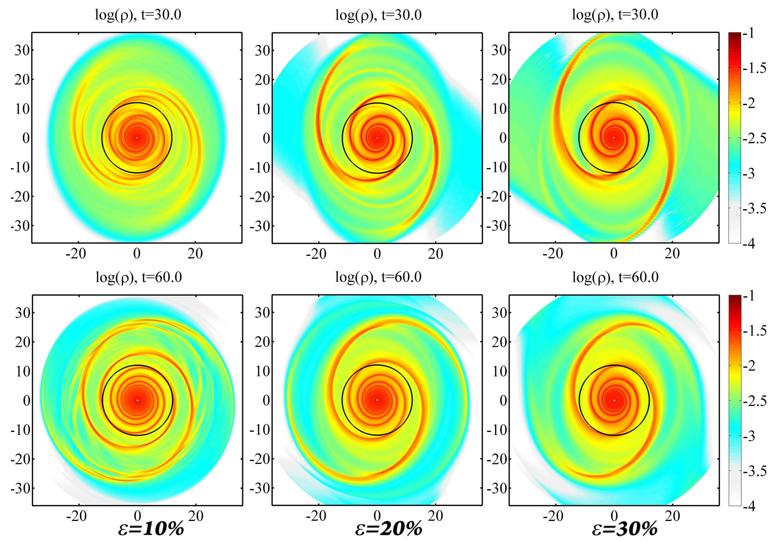

Fig. 3. Gas density distribution $\lg(\sigma(r, \varphi))$ in the model with $Q_{\mathrm{T}} = 2.8$ at time instants $t = T_0$ (top row) and $t = 2T_0$ (bottom row), where T_0 is the disk rotation period at the outer edge. The columns represent three values of the DM halo potential non-axisymmetry parameter ε. The black circle shows the optical size.

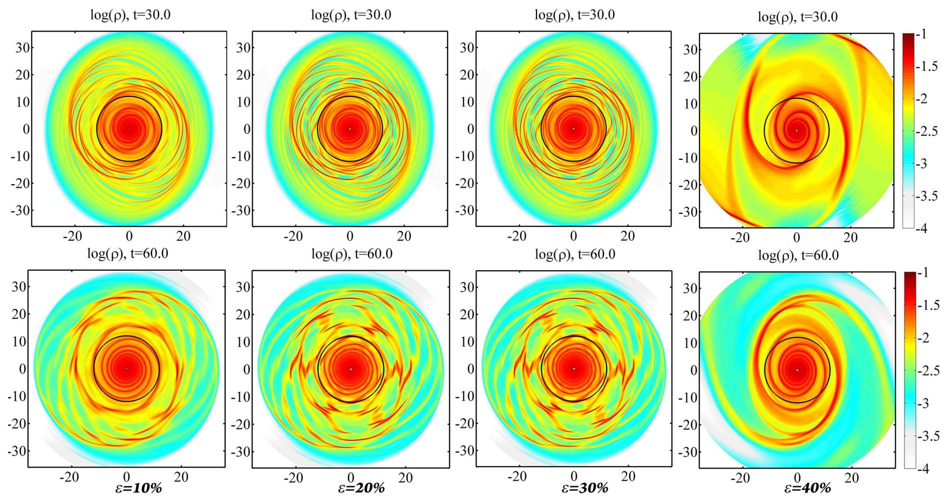

Fig. 4. Same as in Fig. 3, but for the model with $Q_{\mathrm{T}} = 1.8$ and various values of ε.

Fig. 3 shows the evolution of the gas surface density $\lg(\sigma(r, \varphi))$ for three models with different values of the DM halo potential non-axisymmetry parameter, $\varepsilon = 0.1, 0.2, 0.3$ (three columns), at different time steps, $t = T_0$ and $2T_0$ (two rows), where T_0 is the rotation period at the outer edge of the disk. These are the results of the evolution of non-self-gravitating disk characterized by the value of Toomre's parameter $Q_{\mathrm{T}} = 2.8$. A nice two-arm spiral structure forms in all these models.

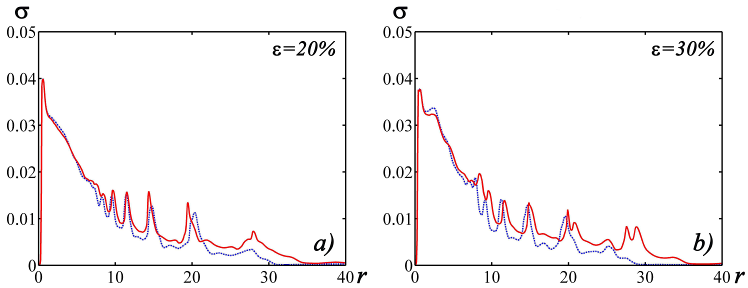

Fig. 5. Gas density distribution $\sigma(x, y)$ along the x- (the dotted lines) and y-axis (the solid lines): (a) $\varepsilon = 0.2$, $\varepsilon_\rho = 0.11$; (b) $\varepsilon = 0.3$, $\varepsilon_\rho = 0.2$, where ε_ρ is the gas density non-axisymmetry and ε is the non-axisymmetry of the DM halo potential.

The spiral pattern develops beyond the optical radius which is equal to 12 kpc. Spiral arms are more clear and have larger amplitude for models with higher DM halo non-axisymmetry ε.

We performed a similar set of simulations for a more massive gaseous disk characterized by a lower value of Toomre's parameter, $Q_{\rm T} = 1.8$ (see Fig. 4). It is obvious that outer part of the disk is gravitationally unstable. In such models on small time scales, $< 2T_0$, the two arm pattern forms similarly to the previous case. However, later its disrupts as a result of growing small-scale perturbations. Such perturbations produce many flocculent clumps covering the entire disk ($R > R_{\rm opt}$). The grand design two-armed pattern can remain a stable long-lived structure only in the case of large non-axisymmetry of the DM halo ($\varepsilon > 0.4$).

We now use Equation 2 to write the basic parameter of the non-axisymmetry of the DM halo in the following form:

$$\varepsilon = 1 - \frac{a_x}{a_y}\,, \tag{3}$$

where a_x and a_y are the halo spatial scales along the x and y axes, respectively. We run a set of simulations where ε varies in the range $0.1 - 0.4$. The gravitational stability of the gas disk is controlled by Toomre's parameter

$$Q_T = \frac{c_{\rm s}\kappa}{\pi G \sigma}\,, \tag{4}$$

where κ is the epicyclic frequency, $c_{\rm s}$ is the adiabatic sound speed, σ is the gas surface density, and G denotes the gravitational constant.

It is interesting to compare the spatial scales of the DM halo non-axisymmetry and the shape of the evolving gas distribution. We introduce the following halo density shape parameter:

$$\varepsilon_\rho = 1 - \frac{r_{OX}}{r_{OY}}\,, \tag{5}$$

where r_{OX}, r_{OY} are the radii of the equal density value along the x- and y-axes, respectively (Fig. 5). The density and potential shape parameters can be matched by solving the Poisson equation: the density non-axisymmetry is equal to $\varepsilon_\rho = 0.11$ and $\varepsilon_\rho = 0.2$ for the potential non-axisymmetry parameter $\varepsilon = 0.2$ and $\varepsilon = 0.3$, respectively. It can be seen that the gas density distribution remains relatively round even in the case of large non-axisymmetric external perturbation. In general, the two parameters are linked by the relation $\varepsilon \approx (1.5-2)\,\varepsilon_\rho$. This result is compatible with observational data demonstrating rather round shapes of face-on galaxies.

We have checked how the halo non-axisymmetry affects the evolution of gas. The most fiducial case is the one where the evolution of the galaxy starts from the spherical halo and then ε increases linearly during T_0 up to a chosen value. In such a model, spirals still develop, but this happens at a later time and the amplitude increase is smaller as well. However, at later stages the simulated pattern agrees very well with the hypothesis of simple non-axisymmetric origination.

4. CONCLUSIONS

Our general results can be summarized as follows. Triaxial (or non-axisymmetric) dark matter distribution can lead to the excitation of a spiral pattern in the gaseous component far beyond the optical size of the galaxy. We investigated how the self-gravity of the gas affects such a process. We found that spirals do not form in a massive disk (self-gravitating gas, $Q_{\rm T} \approx 1$). The point is that self-gravitating gas spirals can be generated by interactions with highly non-axisymmetric halo with a semi-axis ratio of about $a_y/a_x = 0.6$ (or $\varepsilon = 0.4$). Numerical simulations demonstrate rather surprising results, because a disk with stronger self-gravitation cannot support a regular two-arm spiral pattern even in the presence of non-axisymmetric dark matter potential. At the same time, the evolution of a less self-gravitating disk is characterized by a regular two-arm spiral pattern (similar to grand design). We argue that regular spiral arms are not stable in a massive and gravitationally unstable outer gaseous disk. Note, however, the importance of cooling processes, fragmentation of gas, and star formation at greater galactocentric distances which remain open questions.

ACKNOWLEDGMENTS. We wish to thank the Referee for many constructive comments that have helped to improve the quality of the paper. The work was supported by the Russian Foundation for Basic Research (grants Nos. 15-02-06204 and 14-22-03006). We also thank Anatoly Zasov for stimulating discussions and useful comments. The numerical simulations were performed at the Research Computing Center of Moscow State University under the Russian Scientific Foundation grant (No. 14-22-00041) and Joint Supercomputer Center of the Russian Academy of Sciences.

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