

The influence of non-minimally coupled scalar fields on the dynamics of interacting galaxies

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We study bar formation in galactic disks as a consequence of the collision of two spiral galaxies under the influence of a potential which is obtained from the Newtonian limit of a scalar–tensor theory of gravity. We found that dynamical effects depend on parameters (α, λ) of the theory. In particular, we observe that the bar is shorter for weaker tidal perturbations, which in turn corresponds to smaller values of λ used in our numerical experiments.

Keywords: Galaxy interaction; bar formation; dark matter; scalar fields.

Estudiamos la formación de barras en discos galácticos como consecuencia de la colisión de dos galaxias espirales bajo la influencia de un potencial de interacción que proviene del límite Newtoniano de una teoría escalar–tensorial de gravitación. Encontramos cómo los efectos dinámicos dependen de los parámetros (α, λ) de la teoría y en particular vemos que la longitud de la barra es menor cuando las perturbaciones de marea son menores, y esto se logra con valor de λ menor en nuestros experimentos numéricos.

Descriptores: Interacción de galaxias; formación de barras; materia oscura; campos escalares.

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1. Introduction

Observations of spiral galaxies indicate that the presence of a central structure called a *bar* is a common feature [1]. The instability of isolated stellar disks in galactic models leads to bar formation and is characterized by Toomre's stability parameter Q [2]. The models with $Q < 1$ are subject to bar formation. However, we are interested in dynamical effects of non-isolated systems which are found in clusters of galaxies. In this regard, it has been suggested that the observed bar in many spirals is the result of the gravitational interaction between two or more nearby galaxies. For instance, Nogushi [3] has found that, during the collision of two galaxies and between the first and the second closest approaches, the disk takes on transient bar shape. The gravitational interaction between the two galaxies gives rise to perturbations in the orbits of the stars that result in the formation of the bar.

Bar formation in the simulations of stellar disks depends upon various simultaneous effects. In the case of collisions, these factors are [4]: rotation curve shape, disk–halo mass ratio, perturbation force and geometry. However, simulations can suffer from numerical effects such as low spatial and temporal resolution, too few particles representing the system and an approximate force model. These effects can be drastic: for example, observations show that bars have typically a length scale close to the exponential length of the disk [5], while the bar's semi-major axis obtained from numerical models is two to four times longer [6, 7].

Recent observational data measured in the Cosmic Microwave Background at various angular scales, in Supernovae Ia, and in the 2dF galactic survey, suggest [8] that the Universe is composed of about 4% baryons in the form of gas and

stars, 26% dark matter (DM) and 70% dark energy, which is a kind of cosmological constant and is responsible today for the accelerated expansion of the Universe. This way, galaxies are expected to possess these dark components and, in accordance with rotation curves of stars and gas around the centers of spirals, this might be in the form of halos, and must contribute to at least 3 to 10 times the mass of the visible matter of spirals.

Regarding to the nature of DM, we know that DM has to be non-baryonic. This is because nucleosynthesis abundances of light elements are only consistent with the above-mentioned baryonic fraction, and this is not sufficient at all to account for rotational velocities of spirals. This fact opens up new possibilities for explaining the nature of DM. In this sense, in a recent paper [9] a model is proposed in which a scalar field (SF) couples non-minimally to gravity to produce locally a modified Newtonian theory of gravity. It turns out that the dynamics is now determined by the Poisson equation coupled to a Klein–Gordon equation for the assumed scalar field in the galaxy. Thus, the boson mass of the scalar field modifies the Newtonian law of attraction, and the dynamics of DM is different from its Newtonian counterpart. In this scalar–tensor theory, potential–density pairs for various halo density profiles were computed.

In the present work we use the above-mentioned results to study the collision process of two spirals, each of which possess a disk, bulge and dark halo, in order to estimate the effects of the modified gravity theory on the bar's length and the orbital decay of galaxies. We first studied dynamical effects on isolated galaxy models for three different interaction scales (λ). We found no significant changes in the morphol-

ogy of models, but we did in the total potential energy. Then, we analyzed the formation of a bar during a parabolic collision of two identical galaxies and compared the results obtained in the SF model with three scales of λ and with a pure Newtonian interaction.

2. Scalar-tensor theory and its Newtonian limit

A typical scalar-tensor theory is given by the following Lagrangian:

$$\mathcal{L} = \frac{\sqrt{-g}}{16\pi} \left[-\phi R + \frac{\omega(\phi)}{\phi} (\partial\phi)^2 - V(\phi) \right] + \mathcal{L}_M(g_{\mu\nu}), \quad (1)$$

from which we obtain the gravity and SF equations. Here $g_{\mu\nu}$ is the metric, $\mathcal{L}_M(g_{\mu\nu})$ is the Lagrangian matter and $\omega(\phi)$ and $V(\phi)$ are arbitrary functions of the SF. According to the Newtonian approximation, gravity and SF are weak, and the velocities of the stars are non-relativistic. Thus, we expect to have small deviations of the SF around the background defined here as $\langle\phi\rangle = 2 \equiv G_0^{-1}$. If we define the perturbation $\bar{\phi} \equiv \phi - 2$, then the Newtonian approximation gives the equations [9, 10]

$$\nabla^2\psi = 4\pi G_0\rho, \quad \nabla^2\bar{\phi} - m^2\bar{\phi} = -8\pi\alpha G_0\rho, \quad (2)$$

where $\psi = \frac{1}{2}(h_{00} + \bar{\phi})$. Here we define $\lambda = \hbar/mc$, the Compton wavelength of the effective mass m of some elementary particle (boson) given through $\omega(\phi)$ and the potential $V(\phi)$, and $\alpha \equiv 1/(3 + 2\omega(\phi))$ is the amplitude of the perturbed SF, $\bar{\phi}$. The above formalism is valid for any potential that can be expanded in a Taylor series around $\langle\phi\rangle$. In what follows we shall use λ instead of m^{-1} . This mass can have a range of values depending on particular particle physics models.

General solutions of Eqs. (2) can be found in terms of the corresponding Green's functions, and the new Newtonian potential is

$$\begin{aligned} \Phi_N &\equiv \psi - \frac{1}{2}\bar{\phi} = -G_0 \int d\mathbf{r}_s \frac{\rho(\mathbf{r}_s)}{|\mathbf{r} - \mathbf{r}_s|} \\ &\quad - \alpha G_0 \int d\mathbf{r}_s \frac{\rho(\mathbf{r}_s) e^{-|\mathbf{r} - \mathbf{r}_s|/\lambda}}{|\mathbf{r} - \mathbf{r}_s|} + \text{B.C.} \end{aligned} \quad (3)$$

Solutions to these equations for point masses are

$$\bar{\phi} = 2\alpha u_\lambda, \quad (4)$$

$$\Phi_N = -u - \alpha u_\lambda, \quad (5)$$

where

$$u = \sum_s \frac{G_0 m_s}{|\mathbf{r} - \mathbf{r}_s|}, \quad (6)$$

$$u_\lambda = \sum_s \frac{G_0 m_s}{|\mathbf{r} - \mathbf{r}_s|} e^{-|\mathbf{r} - \mathbf{r}_s|/\lambda}, \quad (7)$$

with m_s being a source mass. The total gravitational force on a particle of mass m_i is

$$\mathbf{F} = -\nabla\Phi_N = m_i \mathbf{a}. \quad (8)$$

The potential u is the Newtonian part and u_λ is the SF modification which is of the Yukawa type.

3. Initial conditions

We use the Monte-Carlo procedure to construct a galaxy model with a Newtonian potential. A fully self-consistent model in the context of the SF is in preparation. The initial conditions of the galaxies are constructed following the model described by Barnes [11]. In this model, both the bulge and halo are non-rotating, spherically symmetric and with an isotropic Gaussian distribution of velocities characterized by the velocity dispersions σ_b and σ_h , respectively. The units are such that the local ($r \ll \lambda$) gravitational constant is $G = G_0(1 + \alpha) = 1$, and the units of mass, longitude and time are $M = 2.2 \times 10^{11} M_\odot$, $R = 40$ kpc and $T = 250$ Myrs, respectively. The bulge density profile is [12]

$$\rho_b(r) = \frac{M_b a_b}{2\pi} \frac{1}{r(r + a_b)^3}, \quad (9)$$

and the halo density profile is a Dehnen's family member with $\gamma = 0$ [13],

$$\rho_h(r) = \frac{3M_h}{4\pi} \frac{a_h}{(r + a_h)^4}. \quad (10)$$

The disk density profile is exponential [14]

$$\rho_d(r, z) = \frac{M_d}{4\pi a_d^2 z_0} e^{-r/a_d} \operatorname{sech}^2\left(\frac{z}{z_0}\right). \quad (11)$$

Here $M_b = 0.0625$, $M_d = 0.1875$, and $M_h = 1.0$ are the total mass of the bulge, disk, and halo, respectively. The scale lengths of the bulge, halo, and disk are $a_b = 0.04168$, $a_h = 0.1$, and $a_d = 1/12$, respectively, and $z_0 = 0.007$ is the scale height of the disk. The mass distributions were truncated at a radius containing 95% of the total mass, since they extend to infinity. The compound galaxy was sampled with $N = 40960$ equal mass particles. The velocity distribution of the disk is given by the Schwarzschild distribution function with the velocity dispersions $\sigma_R = 2\sigma_z \propto e^{-a_d r}$, and σ_z given by the equilibrium condition of an infinite gravitating sheet; σ_ϕ is calculated from the epicyclic approximation. The Toomre parameter for the initial disk is $Q \approx 1$, so we have a disk which is marginally stable for axisymmetric perturbations, but not, however, against strong non-axisymmetric ones.

Observations suggest that the majority of the interacting galaxies are located on nearly parabolic orbits. For all collisions, disks were located in the plane of parabolic orbits, calculated from parameterized equations of the two-body problem, with a pericentric separation $p = 0.4$, and the time to

pericenter $t_p = 3.0$. The direction of rotation of one of the disks (disk 1) was in the same direction as the corresponding orbital-angular-momentum, *i.e.* direct motion. The other disk (disk 2) was in retrograde motion. The two colliding galaxies are initially identical.

4. Numerical method

For the time evolution we use the Barnes tree code [15] modified to include the Newtonian contribution of the scalar fields as given by Eqs. (4)-(8). The forces were computed with a tolerance parameter $\theta = 0.75$, and including the monopole term only. For the gravitational potential we used the standard Plummer model

$$\Phi \propto -\frac{1}{\sqrt{r^2 + \epsilon^2}}. \quad (12)$$

Here, ϵ is the softening parameter taken in our simulations to be $\epsilon = 0.015$. The equations of motion were integrated using the second order leap-frog algorithm with a fixed time step $\Delta t = 1/256$. With these parameters we obtain a good energy conservation ($< 0.2\%$) and also good angular momentum conservation ($< 0.5\%$) for all runs presented here.

To characterize quantitatively the bar amplitude, we consider the distortion parameter defined as [17]

$$\eta = \sqrt{\eta_+^2 + \eta_\times^2}, \quad (13)$$

where

$$\eta_+ = \frac{I_{xx} - I_{yy}}{I_{xx} + I_{yy}}, \quad \eta_\times = \frac{2I_{xy}}{I_{xx} + I_{yy}}, \quad (14)$$

and

$$I_{ij} = \sum_{k=1}^N m_k x_k^i x_k^j, \quad i, j = (x, y). \quad (15)$$

The particles that are outside of the spatial region of the original disk can affect the parameter under study. For instance, if we calculate the distortion parameter using all the particles in the disk, we have in both cases similar evolution curves. Therefore, to avoid the noise, we exclude particles that are outside of the original radius of the disk.

5. Results

We first study isolated galaxy models with different values of λ . We consider four sets of simulations followed up to time $t = 8.0$. The parameters and results of runs are presented in the table, where E_0 and \bar{E} are the initial and total mean energies, and $\Delta E/E_0$ is the relative change of the total energy during the evolution with respect to its initial value. Though the scale of interaction λ and magnitude of α are unknown, we choose their values arbitrarily such that λ is equal to the cutoff radius of the disk, bulge and halo for models A1, A2 and A3, respectively, and a fixed amplitude of the SF, $\alpha = 1$.

TABLE I.

Run	λ	\bar{Q}	$ E_0 $	$ \bar{E} $	$ \frac{\Delta E}{E_0} , \%$	$\bar{\eta}$
A1	0.4	1.0	0.7279	0.7277	0.066	0.030
A2	1.0	0.9	0.9511	0.9509	0.048	0.033
A3	6.0	0.9	1.1632	1.1630	0.039	0.042
A4	∞	1.0	1.2234	1.2232	0.036	0.045

The larger λ makes the contribution of the SF weaker for a fixed galactic size. For $\lambda = \infty$, one obtains the Newtonian case, model A4. Previous studies of protogalactic interactions under the influence of this SF [16] were made for scales less than those considered here.

All models show good energy conservation (see table). The presence of the SF decreases the total potential energy due to a shallower potential well at distances $r > \lambda$. The initial models reaccommodate rapidly due to potential modification, *i.e.*, shifts to a new equilibrium state. At the end of the evolution, the components of galaxy models with the SF became slightly more extended. The velocity profiles of the components match the Newtonian ones up to $r \approx \lambda$. For $r > \lambda$ there is a slow decay in velocities, since the effective gravitational constant decreases. The distortion parameter shows a nearly equal noise level of surface density of the disks. The evolution of Toomre's local stability parameter Q shows a slow decay from $Q \approx 1$ to $Q \approx 0.9$, with mean values presented in the table for each run.

Then, we proceed to study the interaction of two equal galaxy models. During the orbital decay we analyze the bar's strength for different values of λ . Because the equilibrium galaxy models were constructed with Newtonian potential, we relax them up to time $t = 1.0$ with a modified SF potential in order to reach a new equilibrium state for a given λ . Then we place relaxed galaxies on parabolic orbits and let them interact.

The results are as follows. The first encounter occurs at time $t \approx 3.0$. This is the time of major transfer of orbital angular momentum, and then disk 1 forms a strong bar, while disk 2 is in retrograde motion and develops a very weak bar. Fig. 1 (left) presents the separation between the centers of mass, p , of two galaxies as a function of time. All runs, except A1, after several close approaches merge and form a remnant. In the run with model A1, after the first approach the galaxies separate such a large distance that they will never encounter again. This is because the weaker the gravity, the lessable the galaxies are to become bound: at distances larger than λ , the potential diminishes in comparison with the pure Newtonian. In runs A2 and A3, the SF causes just a retardation of the subsequent interactions. The simulation with model A3 is practically identical to the Newtonian one.

In order to analyze the bar formation, we consider following only disk 1. In Fig. 1 (right) we plot the distortion parameters η as a function of time for runs with galaxy models A2 and A4 only. As a consequence of gravity modification, the

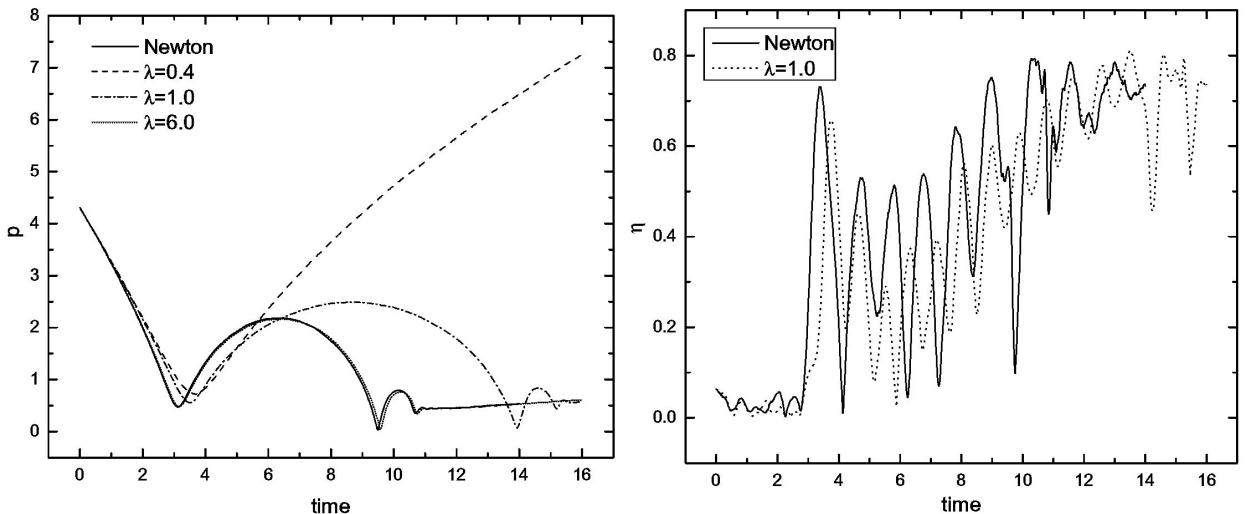


FIGURE 1. Left: The separation between the centers of mass of two galaxies as a function of time. Right: Evolution of η for two collision runs with models A1 and A3.

galaxies do not approach each other too closely as happens in the Newtonian run. Thus, weaker perturbations make the bar shorter. The run with galaxy model A3 is very similar to the Newtonian case. The bar's phases are displaced due to orbit modification.

6. Conclusions

From simulations of isolated galaxy models with a different λ , we can see that the addition of a non-minimally coupled SF slightly modifies the equilibrium of the Newtonian model, acting as a small perturbation, and it diminishes the total potential energy for $r > \lambda$, since the effective gravitational constant decreases in this range. Our results show that the interaction of galaxies with the SF is weaker in comparison with the Newtonian case. We have found that the inclusion of the SF changes dynamical properties such as collision time, bar

morphology, and in general the remnant properties. All these changes depend on the pair (α, λ) , which on the other hand, can be constrained from observations. For instance, the duration of interaction cannot be larger than the age of the Universe, implying constraints on values of G_0 , which depends on G and α . These constraints can be provided from statistical data on the fraction of observed interacting galaxies. A wide range of parameters should be investigated and higher resolution must be used in simulations in order to make predictions for particular interacting models. Further investigations with more particles and self-consistent initial models are under way.

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