Revista Mexicana de Astronomía y Astrofísica, **39**, 113–118 (2003)

GALAXY FORMATION SIMULATIONS WITH SCALAR FIELD DARK MATTER

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Received 2002 July 23; accepted 2003 March 15

RESUMEN

Presentamos una serie de simulaciones para la formación de galaxias usando un modelo cosmológico con campo escalar en el cual la materia obscura esta modelada por un campo escalar Φ. En el modelo de materia obscura escalar (SFDM), la materia obscura consiste de una partícula ultra ligera con una masa de $m_\Phi \sim 10^{-23}\,$eV. Puesto que en el modelo SFDM se recuperan todos los éxitos del modelo de materia obscura fría, esto sugiere que el campo escalar pudiera ser un buen candidato de materia obscura en los halos de galaxias. En este trabajo hacemos algunas simulaciones para la formación de la parte luminosa de galaxias usando el modelo de SFDM. Suponemos que una fluctuación de materia obscura se forma y evoluciona atrayendo materia luminosa alrededor de ella. Bajo estas condiciones, encontramos que la parte luminosa evoluciona y forma objetos con brazos espirales, y luego evoluciona a objetos con simetría circular, los cuales se parecen mucho a las galaxias espirales.

ABSTRACT

We present simulations of galaxy formation using a scalar field cosmological model in which the dark matter is modeled by scalar field Φ. In the Scalar Field Dark Matter (SFDM) model the dark matter consists of an ultra-light particle, with mass $m_\Phi \sim 10^{-23}\,$eV. Since in the SFDM model all the successes of the standard cold dark matter model are recovered, this suggests that the scalar field could be a good candidate for the dark matter in galaxy halos. In this work, we perform simulations for the formation of the luminous part of galaxies using the SFDM model, supposing that a dark matter fluctuation forms and evolves, attracting the luminous matter around it. Under these conditions, we find that the luminous matter evolves and forms objects with spiral arms, and later evolves into an object with circular symmetry, looking very similar to the observed spiral galaxies.

Key Words: **DARK MATTER — GALAXIES: EVOLUTION — GALAXIES: FORMATION — GALAXIES: HALOS**

1. INTRODUCTION

One of the most interesting open question in physics at the moment is without doubt that of the nature of the dark matter in the Cosmos. In the last years the Lambda Cold Dark Matter (ΛCDM) model has gained a remarkable success for explaining most of the astronomical observations (for a recent review see Primack 2002). For example, at th cosmological level, the ΛCDM model has been able to explain the formation of the large scale structure of the Universe, from superclusters of galaxies to galaxies. The most promising candidates for being the dark matter of the Universe are particles which interact very weakly with the rest of the matter with some mass associated to them. They are usually called WIMPs (weak interacting massive particles). However, high resolution simulations using CDM have shown that these candidates present some problems. For example, they cannot explain the observed the smoothness of the galactic-core matter densities, since high resolution numerical simulations with standard CDM predict density profiles with cusps (see for example Firmani et al. 2001; Moore et al. 1998 or, for more recent observations in LSB Galaxies, see de Blok et al.

2001; MacGaugh, Rubin, & de Blok 2001; de Blok, MacGaugh, & Rubin 2001. For comparision with theory and obsevations see Binney & Evans 2001; Blais-Ouellette, Carignan, & Amram 2002; Trott & Wesbster 2002; Salucci, Walter, & Borriello 2002). This is the reason why we need to look for alternative candidates that can explain the structure formation at cosmological level, the observed amount of dwarf galaxies, and the dark matter density profile in the core of galaxies.

In a recent series of papers, we have proposed that the dark matter in the Universe is of a scalar-field nature with a strong self-interaction (Guzmán & Matos 2000; Matos & Guzmán 2000, 2001; Matos, Guzmán, & Núñez 2001; Matos & Ureña-López 2000, 2001). The scalar field has been proposed as a viable candidate, since it mimics standard CDM above galactic scales very well, reproducing most of the features of the standard ΛCDM model (Goodman 2000; Peebles 2000; Matos & Ureña-López 2000, 2001). Moreover, at galactic scales, the scalar field model presents some advantages over the standard ΛCDM model. For example, it can explain the observed scarcity of dwarf galaxies since it produces a sharp cut-off in the Mass Power Spectrum. Also, its self-interaction can, in principle, explain the smoothness of the energy density profile in the core of galaxies (Matos & Ureña-López 2001, 2002; Ureña-López, Matos, & Becerril 2002). The key idea of the SFDM scenario is that the dark matter responsible for structure formation in the universe is a real, minimally coupled scalar field, Φ, with self-interactions parametrized by a potential energy of the form

$$V(\Phi) = V_0\Big(\cosh\big(\lambda\sqrt{\kappa_0}\Phi\big) - 1\Big), \tag{1}$$

where V_0 and λ are the only two free parameters of the model, $\kappa_0 = 8\pi G$ (we employ natural units where $\hbar = c = 1$, such that $\kappa_0 = 8\pi/m_{\rm pl}^2$, where $m_{\rm pl}$ is the Planck mass). The effective mass of the scalar field is given by $m_\Phi^2 = \kappa_0 V_0 \lambda^2$. A minimal coupling avoids the strong restrictions imposed by the equivalence principle on scales of the order of the solar system.

The advantage of the SFDM model is that it is insensitive to initial conditions and the field behaves as CDM once it begins to oscillate around the minimum of its potential. In this case, it can be shown (Matos & Ureña-López 2001, 2002) that the SFDM model is able to reproduce all the successes of the standard ΛCDM model above galactic scales. Furthermore, it predicts a sharp cut-off in the mass power spectrum due to its quadratic nature, thus explaining the observed dearth of dwarf galaxies, in contrast with the excess predicted by high resolution N-body simulations with standard CDM (Matos & Ureña-López 2001). The strong self-interaction of the scalar field results in the formation of solitonic objects called 'oscillatons', which have a mass of the order of a galaxy but do not exhibit the cusp density profiles characteristic of standard CDM (Ureña-López 2002; Alcubierre, Guzmán, Matos et al. 2002; Alcubierre, Becerril, Guzmán et al. 2002; Ureña-López, Matos, & Becerril 2002). The best-fit model to the cosmological data can be deduced from the current densities of dark matter and radiation in the universe and from the cut-off in the mass power spectrum that constrains the number of dwarf galaxies in clusters. The favored values for the two free parameters of the potential (1) are found to be (see Matos & Ureña-López 2001):

$$\lambda \simeq 20.28, \tag{2}$$

$$V_0 \simeq (3 \times 10^{-27}\, m_{\rm pl})^4. \tag{3}$$

This implies that the effective mass of the scalar field should be $m_\Phi \simeq 9.1 \times 10^{-52}\, m_{\rm pl} = 1.1 \times 10^{-23}\,$eV.

An important feature of the potential (1) is that it is renormalizable and exactly quantizable (Halpern & Huang 1995, 1996; Branchina 2001). Furthermore, the scattering cross section by mass of the scalar particles, $\sigma_{2\rightarrow 2}/m_\Phi$, can be constrained from numerical simulations of self-interacting dark matter that avoid high-density dark matter halos. This effectively constrains the renormalization scale, Λ_Φ, of the potential to be of the order of the Planck mass, $\Lambda_\Phi \simeq 1.93 m_{\rm pl} = 2.15 \times 10^{19}$ GeV (Matos & Ureña-López 2002).

In a recent work (Alcubierre et al. 2002), we showed that the scalar field collapses to form objects very similar to typical halos of galaxies. Furthermore, the critical mass of the collapse is just

$$M_{\rm crit} \simeq 0.1 \frac{m_{\rm pl}^2}{\sqrt{\kappa_0 V_0}} = 2.5 \times 10^{13}\, M_\odot. \tag{4}$$

which implies that when a scalar field collapses, it will do it with the mass of the typical halo of a galaxy. In these numerical simulations the luminous matter does not curve the space-time; this matter is considered to be like test particles in the system. Due to the fact that the scalar field is a field, it is not possible to perform N-body simulations with this paradigm.

Instead of that, in this work we perform numerical simulations to form objects like galaxies, using as background the object formed by the collapse of the scalar field. In other words, we suppose that the halo of the galaxy is the main contributor to the formation of the galaxy, and also that the luminous matter adapts to the potential formed by 90% of the galaxy, i.e., the halo. This work intends to be the first of a series of numerical simulations in order to construct realistic collapses of the scalar field, together with the luminous matter. In this work we perform the most simple approximation. We suppose that the halo forms first; after that, the luminous matter goes around the halo and forms an object. In Matos & Guzmán (2001) we have shown that the background of the scalar field after collapses can be well approximated by

$$ds^2 = \frac{A_0\, dr^2}{(1-2M/r)} + r^2\, d\Omega^2 - (r^2+b^2)^{v_{\rm a}^2}\left(1-\frac{2M}{r}\right) dt^2, \tag{5}$$

where $d\Omega^2 = d\theta^2 + \sin\theta\, d\varphi^2$. Here M is a constant and $A_0 = 1 - v_{\rm a}^4$, with $v_{\rm a}$ being the asymptotic velocity of the test particles (stars) in the halo. M is the mass of a central compact object, for example a black hole, which interacts with the luminous matter going around very close to the black hole. In this work, we do not take into account the interaction of the central black hole, because it only alters the trajectories of the stars very close to the center of the galaxy; it is not essential for the behavior of the stars in the disc nor in the halo. This fact can also be seen writing the value of the parameter M. For a central black hole about $10^6\, M_\odot$, the mass parameter $M \sim 1.5\times 10^6\,$km $\sim 10^{-8}\,$kpc, while the parameter $b \sim 3\,$kpc.

Metric (5) contains some nice properties. The most important one is that the tangential velocity for test particles, (the rotation curves for stars) behaves in a very similar manner as in the pseudo-isothermal model for halos (Persic, Salucci, & Stel 1996; de Blok et al. 2001). To see this, we follow Chandrasekhar (1983) (see also Matos et al. 2002) where the tangential velocity of the test particle is given by

$$v^{\rm tangential} = v^\varphi = \sqrt{\frac{rB'}{2B}}, \tag{6}$$

where B is the 00 component of the metric and $'$ means derivative with respect to r. For metric (5), $B = (r^2+b^2)^{v_{\rm a}^2}\,(1-2M/r)$; thus, the rotation curves for test particles are given by

$$(v^\varphi)^2 = \frac{v_{\rm a}^2 r^2}{(r^2+b^2)} + \frac{M}{(r-2M)}. \tag{7}$$

The first term of equation (7) is the velocity of the rotation curves for a pseudo-isothermal distribution

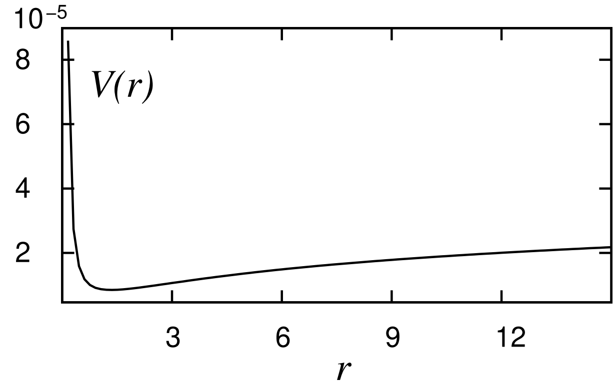

Fig. 1. The effective potential (11) derived from the calculation of the geodesics. Here we show the plot of the potential using the values for A, B given in the text, with typical parameter values: $B = 0.00202262288$, $A \approx 1$, $M = 0$, $b = 2.119$, $A_0 = 1$, and $v_a = 0.00283$.

of matter; its corresponding Newtonian density is given by

$$\rho = \frac{v_{\rm a}^2\left(r^2 + 3\,b^2\right)}{4\pi\, G\left(r^2+b^2\right)^2}. \tag{8}$$

The second term of equation (7) corresponds to the rotation curves of a particle close to the gravitational field of a black hole. In this work we set $M = 0$, neglecting the contribution of a possible black hole in the center of the galaxy.

Thus, the SFDM model has the following features: (a) the SFDM model is able to reproduce all the successes of the standard ΛCDM model above galactic scales; (b) at the galactic level, the scalar field collapses with a preferred mass of order of $M_{\rm collapse} \simeq 10^{12}\, M_\odot$; (c) metric (5) represents the space-time of a collapsed scalar field, the rotation curves of this object corresponds to the pseudo-isothermal halo of a galaxy. This is the reason why we expect that the halo of a galaxy can be modeled by the gravitational field of a scalar field.

For future work, we derive in § 2, the effective potential from metric (5), even taking into account parameter M. In § 3 we explain the method used for the numerical simulations and show them, and in § 4 we give some conclusions.

2. THE EFFECTIVE POTENTIAL

In this section we derive the effective potential of metric (5). For test particles on the disc of the galaxy $\theta = \pi/2$, then the geodesics of the metric are given by

$$geo_r = \ddot{r} - \frac{M\dot{r}^2}{r\,(r-2M)} - \frac{(r-2M)\,\dot{\varphi}^2}{A_0} + \left(r^3 A_0 \left(r^2+b^2\right)\right)^{-1} \left(r^2+b^2\right)^{v_{\rm a}^2} (r-2M) \left(v_{\rm a}^2 r^2 (r-2M) + M\left(r^2+b^2\right)\right) \dot{t}^2 \tag{9a}$$

$$geo_\varphi = \frac{1}{r^2}\left(r^2\dot{\varphi}\right) \tag{9b}$$

$$geo_t = \left(\left(r^2+b^2\right)^{v_{\rm a}^2} (1-2M/r)\right)^{-1} \left(r^2+b^2\right)^{v_{\rm a}^2} \left(1-\frac{2M}{r}\right) \dot{t}, \tag{9c}$$

where dot means derivative with respect to the proper time of the test particle. Equation (9) can be reduced to

$$\frac{1}{2}\dot{D}^2 + V = E, \tag{10a}$$

$$r^2\dot{\varphi} = B, \tag{10b}$$

$$\left(r^2+b^2\right)^{v_a^2}\left(1-\frac{2M}{r}\right)\dot{t} = A, \tag{10c}$$

where E, A and B are integration constants for each orbit, $\dot{D} = \dot{r}\,(1-2M/r)^{-1/2}$ is the proper radial distance of the test particle, and V is the effective potential given by

$$A_0 V = \frac{1}{2}A^2\left[v_a^2 \ln(r^2+b^2) + \ln(1-2M/r)\right] + \frac{B^2}{2r^2}. \tag{11}$$

Note that the equation (10a) represents the Newtonian energy equation, (10b) is the conservation of the angular momentum of the test particle, and (10c) is the conservation equation of the proper time; it is the relativistic contribution to the Newtonian laws.

Equations (10) and (11) determine the orbit of a test particle (a star) around the galaxy. Fortunately, from observations we know the distribution of the test particles around the galaxy: its density profile is exponential. Using this fact, we can estimate the angular momentum B and constant A from this distribution. In order to do so, observe that the proper time of the test particles is defined as

$$-d\tau^2 = \left[v^2 - \left(r^2+b^2\right)^{v_a^2}\left(1-\frac{2M}{r}\right)\right] dt^2, \tag{12}$$

where v is the velocity of the test particle: $v^2 = A_0\dot{r}^2/(1-2M/r) + r^2\dot{\theta}^2 + r^2\sin^2\theta\,\dot{\varphi}^2$. Using this definition we can compare it with (9) to obtain

$$\dot{t}^2 = \frac{1}{\left(r^2+b^2\right)^{v_{\rm a}^2}(1-2M/r) - v^2} = \frac{A^2}{\left(r^2+b^2\right)^{2v_{\rm a}^2}(1-2M/r)^2}. \tag{13}$$

Using the fact that $v \ll 1$, we can estimate the value of the parameter A to be

$$A \sim \sqrt{\left(r^2+b^2\right)^{v_{\rm a}^2}(1-2M/r)}. \tag{14}$$

Furthermore, since B can be interpreted as the angular momentum of the test particle, then $B = Dv$. In this case we can estimate the value of the integration parameters using the distribution of the luminous matter in a galaxy

$$v^2 = v_{\rm a}^2\beta\frac{1.97x^{1.22}}{\left(x^2+0.78^2\right)^{1.43}}, \tag{15}$$

where $x = r/R_{\rm op}$ and β and $R_{\rm op}$ are parameters which fit the luminous matter of a specific galaxy. With equations (10), (14) and (15) we can completely determine the orbits of a test particle in the galaxy we are modeling. β is given by the model of the luminous matter and b is given by the model of the scalar dark matter.

3. NUMERICAL SIMULATIONS

In Figure 1 there is a plot of the effective potential (10) with typical values used in numerical propagations: $B = 0.00202262288$, $A \approx 1$, $M = 0$, $b = 2.119$, $A_0 = 1$, and $v_{\rm a} = 0.00283$. The values of B are calculated for each particle at their initial position, and kept constant during the simulation.

We generated an initial distribution of 1500 point particles in a random way and propagated in time these particles by using a second-order finite-differences version of equations (10), (14), and (15). In Figures 2 to 6 there are snapshots of some evolutions (for movies of the simulations, see http://www.fis.cinvestav.mx/~tmatos/movies.html). The effective potential causes the particles to oscillate in r around its minimum, and the position-dependent initial values of the angular momentum cause the distribution of particles to conform to a spiral-like shape as time increases. The final distribution resembles a uniform random distribution around the origin.

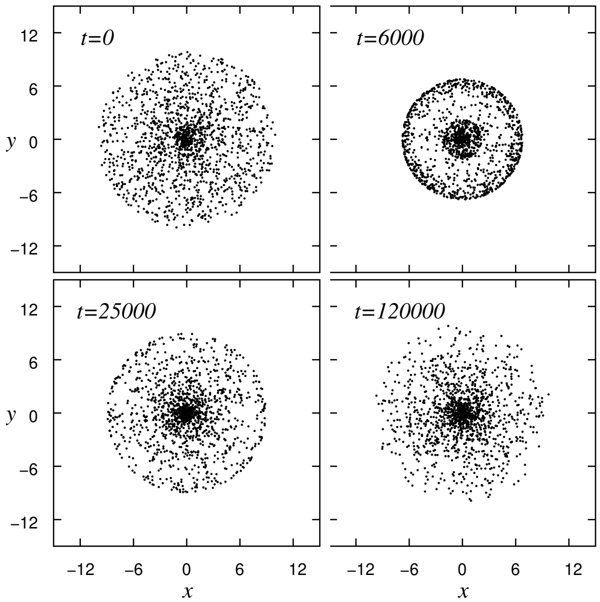

Fig. 2. Four snapshots of the evolution of a collection of particles. Numerical simulation for the formation of the luminous matter of a galaxy. Here we start with a baryonic perturbation centered in the center of the dark matter halo density and with circular symmetry. Observe how the luminous matter tends to form a circular galaxy. After a while the object remains stable.

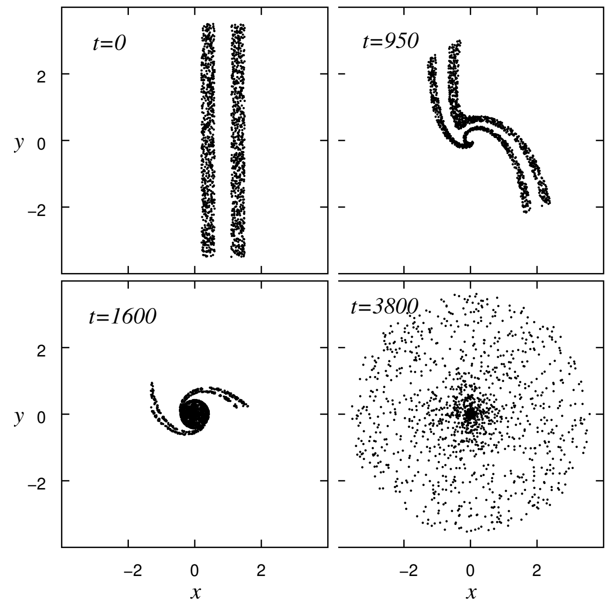

Fig. 4. As in Fig. 2 but now starting with two line baryonic perturbations. Observe again how the perturbations tend to form spiral arms, and later they tend to form a circular object. The third plot in this figure is an object which looks very similar to a spiral galaxy.

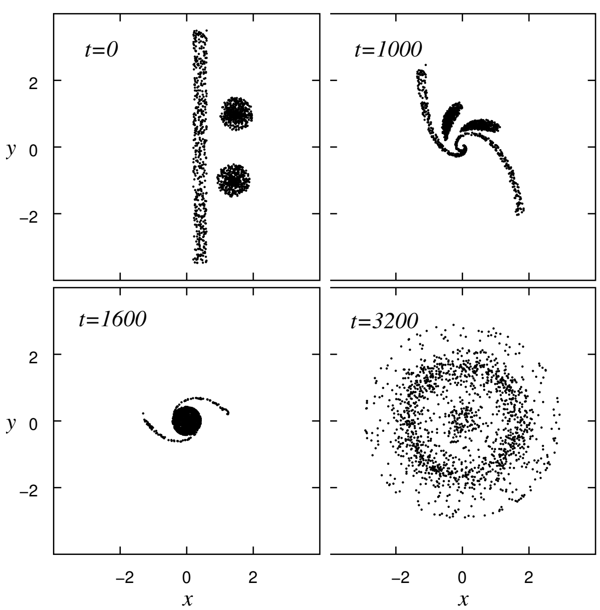

Fig. 3. As in Fig. 2, but now we start with two pertubations with circular symmetry and a baryonic pertubation with a line symmetry. Observe how the pertubations tend to form an object with spiral arms which later tends to be circular, (spherical).

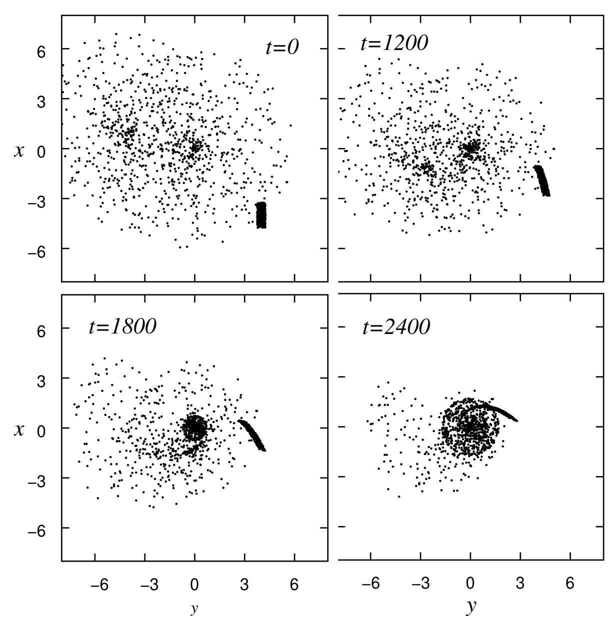

Fig. 5. As in Fig. 2, but now starting with two big baryonic perturbations and two small ones. Again the perturbations tend to form spiral arms, and later they tend to form a circular object.

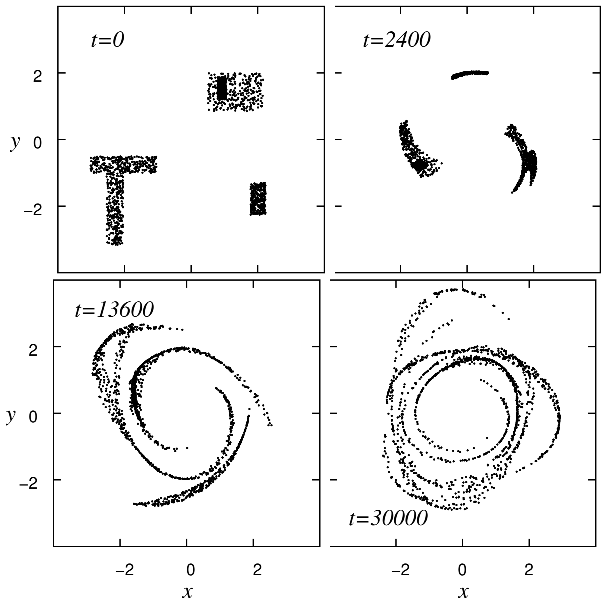

Fig. 6. As in Fig. 2, but now starting with many different baryonic perturbations. Observe how, again, the perturbations tend to form spiral arms and later they tend to form a circular object. It seems as if the initial baryonic perturbations are essential, since the formation of spiral arms and, later, of a circular object is the common evolution of the simulation.

4. CONCLUSIONS

The main idea for the formation of a galaxy is that some primordial fluctuations of baryonic matter, produced during some inflationary period, interact with a collapsed scalar field of mass $\sim 10^{12}\,M_\odot$. In the numerical simulations shown in Figs. 2 to 6, we start with some arbitrary perturbations of the luminous matter in very different ways. We only show the luminous matter while the dark matter is put as the background where the luminous matter is moving. Although we have performed strong approximations, observe that the results are always objects very similar to a galaxy. We suspect that when we eliminate the approximations we have made here, the resulting simulations will be very similar to the objects we have found here, but this is the subject for future work. In any case, from the numerical simulations performed here, we see the formation of objects which remind us of the spiral galaxies observed in the Universe.

We would like to thank E. Gómez and A. Espíritu for technical support. This work was partly supported by CONACyT México, under grants 38495-E and 34407-E.

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