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Simulating Galaxy Formation with Scalar Field Dark Matter

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Abstract.

In this work we consider the formation of galaxies using the scalar field dark matter (SFDM) model. In this model the galactic haloes are astronomical Bose-Einstein Condensate drops of SF. This haloes are characterized by a constant-density core and are consistent with observed rotation curves of dark matter dominated galaxies, a missing feature in CDM haloes resulting from DM only simulations. We include the baryonic component to the SF haloes in a set of grid-based hydrodynamic simulations.

1. INTRODUCTION

Over the last years works on galaxy formation are gradually becoming more and more complete, incorporating a wide array of physical processes. So great progress has been made in the field,but most of this works model the formation of galaxies within the current structure formation paradigm in which the Universe is dominated by a cold dark matter component and a cosmological constant, the ΛCDM cosmological model, that has been successful in reproducing many large scale observable properties of the Universe, however, still faces many challenges from observations of galaxies on small scales. The incorporation of a new kind of DM, different from the one proposed by the CDM holds out the possibility of resolving some of these issues. An alternative scenario that has received much attention is the scalar field dark matter (SFDM) model. The main idea is simple [6], the nature of the DM is completely determined by a fundamental scalar field Φ. In this dark matter and galaxy formation scenario the DM haloes are naturally cored. Robles & Matos [10] found excellent agreement with data of rotation curves for LSB galaxies using the minimum disk hypothesis (neglecting the baryonic component).

In this work we explore the behavior of those rotation curves but now taking into account the baryonic component. We ran some simple simulations evolving the hydrodynamic equations for a gas distribution embedded in a SFDM galactic halo.

2. Basic Setup

The basic theoretical framework states that disk galaxies arises from the gravitational collapse of a rotating protogalactic cloud of gas within the gravitational potential well of the dark halo. The gas eventually settles in centrifugal equilibrium at the center of the halo potential well forming a rotationally supported gas disk. Our basic picture is a rotating distribution of gas within a spherical Dark Matter Halo. The potential is assumed to be generated by a static distribution of dark matter that remains fixed throughout the simulation. We focus on dark matter dominated systems so the self gravity of the gas is ignored.

2.1. Code

The simulations were performed using the latest version of the ZEUS-MP code, released by the Laboratory for Computational Astrophysics. The physics suite in this code includes gas hydrodynamics, ideal MHD, flux-limited radiation diffusion, self gravity, and multispecies advection [9]. In this work we focus in solving only the standard hydrodynamics equations, where the description of the physical state of a fluid element is specified by the following set of fluid equations relating the mass density (ρ), velocity ($\mathbf{v}$) and gas internal energy density (e).

$$\begin{aligned} \frac{D\rho}{Dt} + \rho\nabla\cdot\mathbf{v} &= 0, & (1)\\ \rho\frac{D\mathbf{v}}{Dt} &= -\nabla P - \rho\nabla\Phi, & (2)\\ \rho\frac{D}{Dt}\left(\frac{e}{\rho}\right) &= -P\nabla\cdot\mathbf{v}, & (3) \end{aligned}$$

where the Lagrangean (or comoving) derivative is given by the usual definition:

$$\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla. \tag{4}$$

Spherical polar $(r;\theta;\phi)$ coordinates are used. The simulations were run on a $200\times100\times100$ cell grid.

3. The Dark Matter Halo

The ΛCDM model still faces many challenges from observations of galaxies on small scales. For instance, in the ΛCDM simulations the halos present rising densities towards the central region behaving as $\rho \propto r^{-1}$ well within 1 kpc [9]. On the other hand, several observations suggest that the dynamics (rotation curves) of dwarf and LSB galaxies are more consistent with a constant central density, this is most commonly known as the cusp/core problem [3]. This and other problems motivate the proposal of alternative dark matter models to explain the observed central distribution of galaxies.

An alternative scenario that has received much attention in the last years is the scalar field dark matter (SFDM) model. The main idea is that the nature of the DM is completely determined by a fundamental scalar field Φ [6]. The SFDM model proposes that galactic haloes form by Bose-Einstein condensation of a scalar field (SF) whose boson has an ultra-light mass of the order of $m \sim 10^{-22}eV$.In addition, the Compton length $\lambda_c = 2\pi\hbar/m$ associated to this boson is about $\sim$ kpc that corresponds to the dark halo-size of typical galaxies in the Universe. Thus, it has been proposed that these drops are the haloes of galaxies [8], i:e:, that haloes are huge drops of SF. Within the framework of the SFDM/BEC model exist an exact analytic solution for a static SF configuration, a finite temperature density profile which in the SFDM model represents a DM halo.

$$\rho(r) = \rho_0\frac{\sin^2(kr)}{(kr)^2}, \tag{5}$$

where the central density $\rho_0 = \rho(0)$ and k are fitting parameters. In Figure 1 we show the density profile,. it is in the log-log plot that we can see one of the main features of the

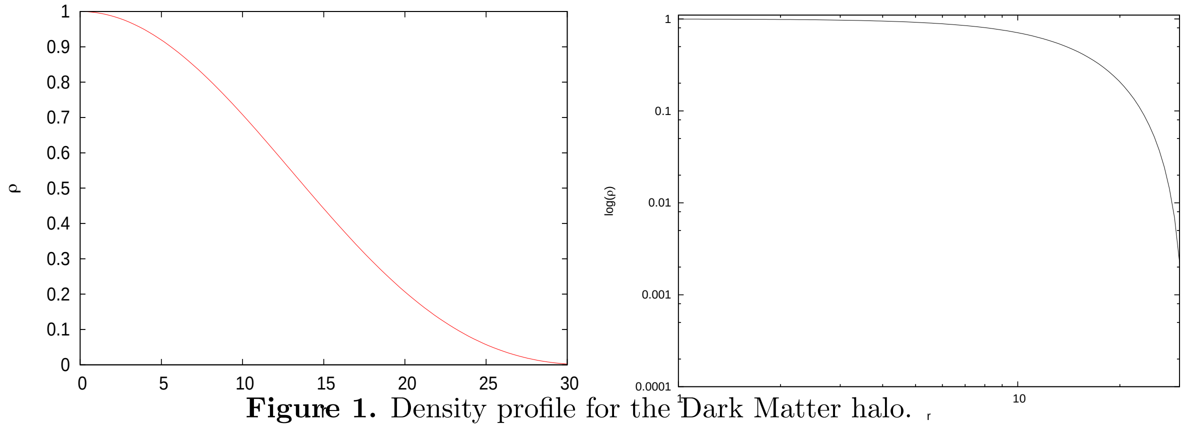

Figure 1. Density profile for the Dark Matter halo.

SFDM/BEC model, a flat core is present in the DM haloes and is explained by the model rather than just be assumed, so in this model the cusp/core problem is not even there in the first place.

From equation (5) and from Poisson's equation one can see that the potential of the DM distribution goes like

$$\phi_h(r) = \frac{GM_h}{a(r_0)}\left(\ln(r) + \frac{\sin(2kr)}{2kr} - Ci(2kr)\right), \tag{6}$$

where Ci is the cosine integral function. It is well known that a logarithmic potential maintains flat rotation curves at large radii, so one of the main features of the SFDM/BEC model is that the rotation curves are flat, which is consistent with the observations of many galaxies.

From equation (5) we obtain the accumulated mass at a radius r and the rotation curve profile

$$M(r) = \frac{2\pi\rho_0}{k^2}\left[r - \frac{\sin(2kr)}{2k}\right], \tag{7}$$

$$v^2(r) = \frac{2\pi\rho_0}{k^2}\left[1 - \frac{\sin(2kr)}{2kr}\right]. \tag{8}$$

4. Results

In this section we present the results of two simulations where the parameters, size and mass, of the DM halo remain the same but the initial distributions of gas are different. In the first configuration we have a rotating sphere of gas and for the second one we have a rotating gas disk. So the gas is embedded in a static DM halo, with the DM density distribution given in equation (5). When we say that the DM halo is static it means that its effect is treated as an external force in the momentum equation for the gas.

From equation (5) we compute the acceleration that the DM halo produces on the gas

$$-\nabla V = \frac{2\pi G\rho_0}{k^2}\left[\frac{1}{2k}\frac{\sin(2kr)}{r^2} - \frac{1}{r}\right]. \tag{9}$$

Also we imprint angular momentum to the initial distribution of gas such that it is in circular orbit in the mid-plane. Here we focus on dark matter dominated galaxies so the amount of gas that we put in the domain is such that it is the 10% of the DM halo mass.

For our first setup the initial distribution of gas is spherical. Figure 2 shows face-on slices of the gas density distribution, each plot is a color map of the gas density with the brightest colors representing the highest values, so the snapshots shows the evolution of the gas through the entire simulation. From first to second snapshot the increase in the density is appreciable, this is because the gas, initially distributed in spherical way, settles down to the mid-plane. Note that, although the initial distribution had azimuthal symmetry, a distinctive spiral pattern emerge in the center of the domain.

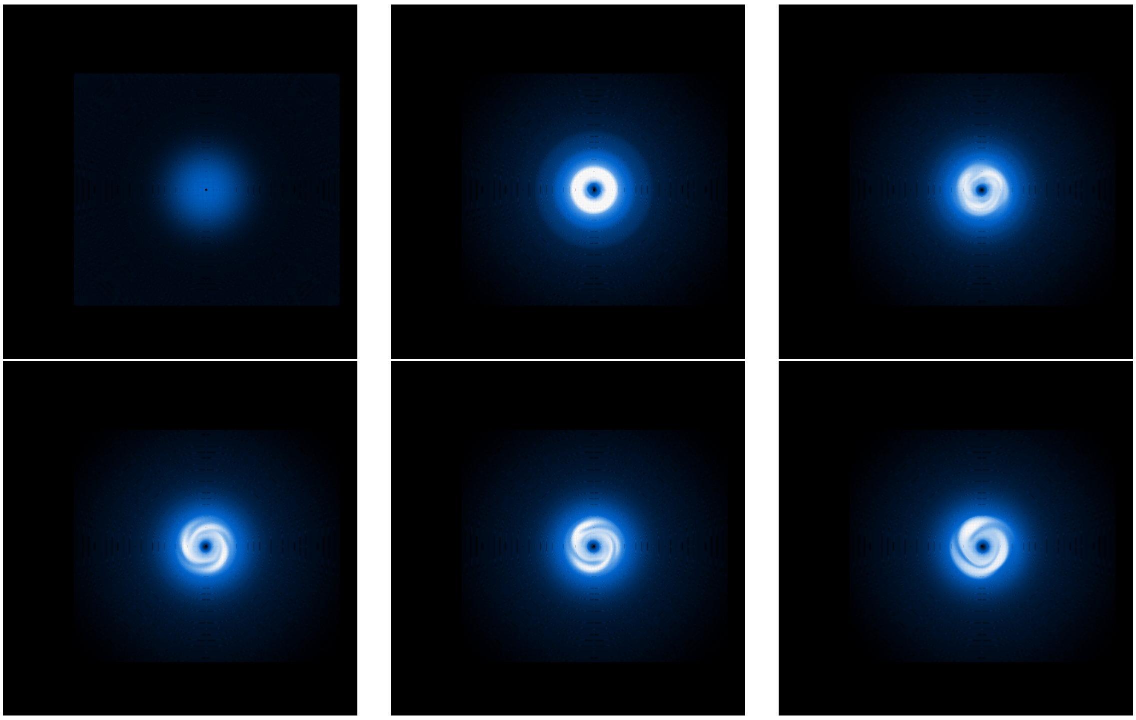

Figure 2. From left to right and from top to bottom we follow the temporal evolution of the gas density, sliced in the direction normal to the axis of rotation.

Meanwhile, Figure 3 shows edge-on slices of the gas density, here we can see the expected behavior for a rotating distribution. We begin with a spherical distribution but with the pass of time the density increase and the gas settles down in a plane perpendicular to the axis of rotation.

Figure 4 shows the temporal evolution of the circular velocity for the gas on the mid-plane, here we can see how the initial velocity drops at the right part of the domain, with the pass of time the right end of the curve rises to maintain a flat profile at the latest stages of the simulation. Clearly we can see that small oscillations appear over the profiles, and the last curve plotted in figure 4 resembles some circular velocity curves observed on LSB galaxies.

For our second setup the size and mass of the DM halo remain the same, but we start with a gas disk rotationally supported. Again, the amount of gas in the disk is such that it is the 10% of the DM halo mass. Very few changes can be seen in the shape of the gas density distribution along the simulation, so we focus on the circular velocity (figure 5).

Comparing the second plot from figure 4 and 5, which represent the simulations in their first

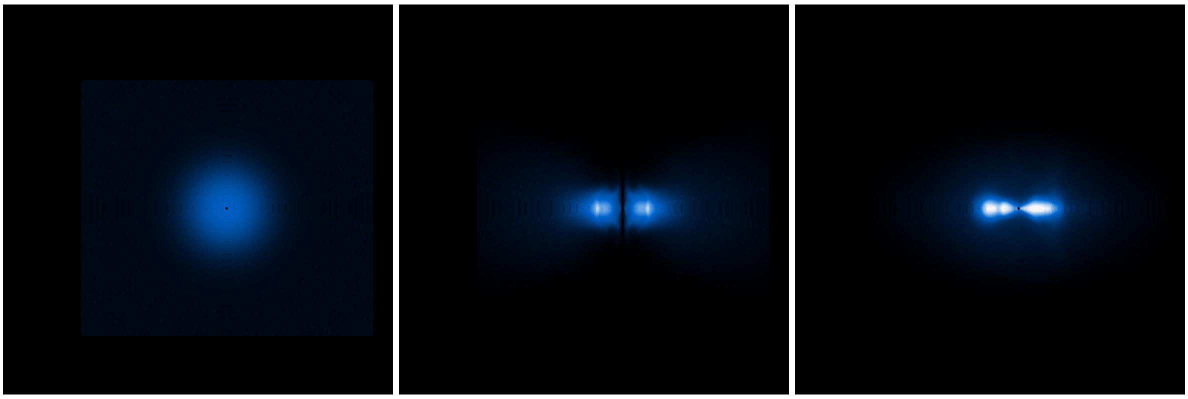

Figure 3. Temporal evolution of the gas density, sliced perpendicular to the midplane.

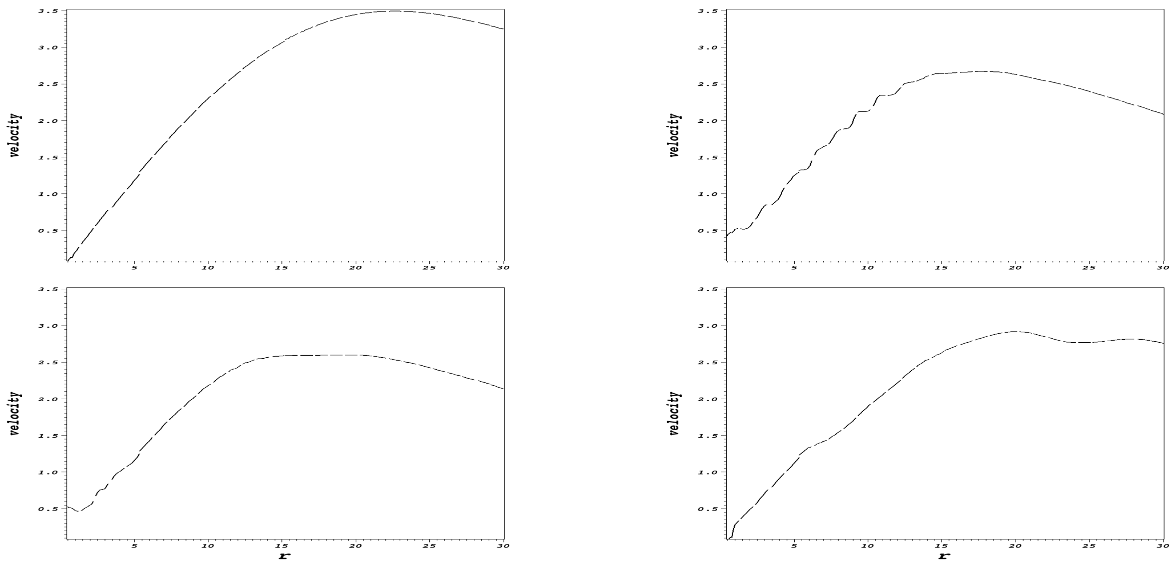

Figure 4. Temporal evolution of the gas circular velocity, taken from the midplane.

stages, we see a slightly different behavior of the curves. This is because at this stage the gas distributions are very different, it is only when the gas in the first simulation settles down to the mid-plane that the curves look very alike (see fourth plot from figure 4 and 5). This means that the final configuration in our first simulation reproduce rotation curves very similar to those seen in the simulation with the gas disk, plus the curves resemble those observed in LSB galaxies. We conclude that with this simple scenario of a rotating spherical distribution of gas embedded in a SFDM galactic halo we can reproduce some of the features seen in dark matter dominated disk galaxies.

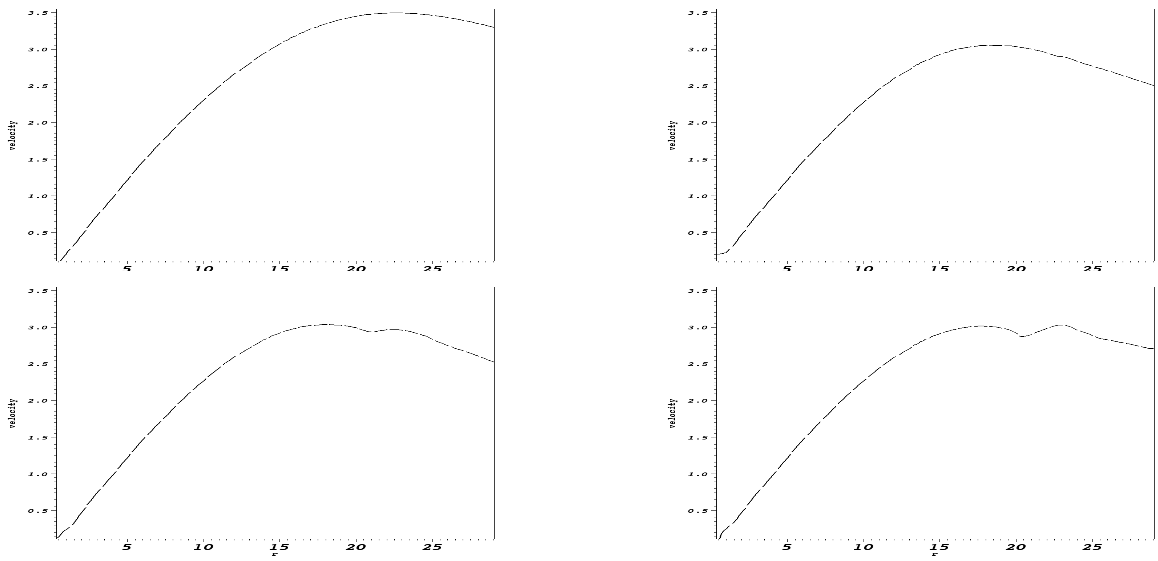

Figure 5. Temporal evolution of the gas circular velocity, taken from the midplane.

5. Conclussions

The problems that CDM faces at galactic scales had prompted the development of alternative DM models. Particularly the scalar field dark matter (SFDM) model has proved to be a serious alternative to ΛCDM. We are exploring the galaxy formation under the SFDM model by adding the baryonic component. Describing the gas with just the standard hydrodynamics equations we found that starting with a distribution of gas that eventually settles in centrifugal equilibrium, the obtained rotation curves resemble those observed in LSB galaxies.

We have performed 3D hydrodynamic simulations with simple physical processes for the gas, and although we argue that huge quantities of feedback events (star formation, supernovas) are not needed, feedback must be added to our simulations but in a way different of that used in CDM-based simulations because we are not trying to change the shape of the DM density profiles through feedback processes. In future works we will do this in an attempt to simulate realistic galaxies within the SFDM model.

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