The influence of scalar fields in protogalactic interactions

M. A. Rodríguez-Meza, Jaime Klapp† and Jorge L. Cervantes-Cota‡
Departamento de Física,
Instituto Nacional de Investigaciones Nucleares (ININ)
Apartado postal 18–1027, México D.F. 11801, México
and
Heinz Dehnen
Fakultät für Physik
Universität Konstanz, Postfach 5560 M 677
D-78434 Konstanz, Germany

Abstract

We present simulations within the framework of scalar-tensor theories, in the Newtonian limit, to investigate the influence of massive scalar fields on the dynamics of the collision of two equal spherical clouds. We employ a SPH code modified to include the scalar field to simulate two initially non-rotating protogalaxies that approach each other, and as a result of the tidal interaction, intrinsic angular momentum is generated. We have obtained sufficient large values of $J/M$ to suggest that intrinsic angular momentum can be the result of tidal interactions.

*On leave from Instituto de Física, Benemérita Universidad Autónoma de Puebla.
†e-mail:klapp@nuclear.inin.mx
‡e-mail:jorge@nuclear.inin.mx
1 Introduction

In recent years there has been achieved important progress in understanding the dynamics that led to the formation of galaxies. Two and three dimensional N-body simulations of galaxies and protogalaxies have been computed using up to a few millions of particles, giving a more realistic view of how galaxies, quasars, and black holes could have formed (Barnes & Hernquist 1992, Barnes 1998).

The Universe’s composition at the time galaxies formed could be, theoretically, very varied, including baryonic visible and dark matter, non baryonic dark matter, neutrinos, and many cosmological relics stemming from symmetry breaking processes predicted by high energy physics (Kolb & Turner 1990). All these particles, if present, should have played a role in the structure formation. Then, galaxies are expected to possess dark matter components and, in accordance with the rotational curves of stars and gas around the centres of spirals, they are in the form of halos (Ostriker & Peebles 1973) and must contribute to at least 3 to 10 times the mass of the visible matter (Kolb & Turner 1990).

Whatever the Universe composition was, protogalaxies were originated due to a spectrum of scale-invariant perturbations (Harrison 1970; Zel’dovich 1972) that was present within the cosmological background at the beginning of structure formation; the inflationary cosmology is the most convincing scenario that explains its origin (Mukhanov et al 1992). Protogalactic structures began to acquire some momenta, e.g. tidal torques (Fall & Efstathiou 1980), because of local gravitational instabilities to provoke plenty of collisions, mergings, fly-bys, etc, between these original, cosmic structures. As a result of their evolution, galaxies, as we presently know them, must have formed. The dynamics of protogalaxies has been studied intensively, for a review see Barnes & Hernquist (1992). There has been much interest to understand how galaxies acquired their present features, especially how their internal angular momentum (spin) has been gotten, $J/M \sim \mathcal{O}(10^{30})$ cm$^2$/s.

A very important issue about it is how the transfer of angular momentum between protogalaxies took place to give rise to the observed elliptical and spiral galaxies with their known mass and rotational properties. As an initial condition can be thought that protogalaxies were gravitationally isolated. However, there are some indications that the orbital angular momentum in spiral galaxies in pairs is few times larger than their spins, so pairs seem to be not dynamically isolated (Oosterloo 1993). Part of this angular momentum
could had its origin in the cosmic expansion (Caimmi (1989,1990), Andriani & Caimmi (1994)), where it has been computed the torques at the beginning of strong decoupling from the Hubble flow of spherical-symmetric density perturbations. Moreover, observations of spin angular momentum of various thousands of disc galaxies are compatible with the mechanism of generation of spin via tidal torques (Sugai & Iye 1995). Other theoretical and numerical studies of evolution of angular momentum of protogalaxies from tidal torques are in line with observations (Chernin 1993, Catelan & Theuns 1996).

In the present work we investigate how the transfer of orbital to spin angular momentum is achieved when two equal, spherical clouds pass by, and in some cases when they collide; this type of interactions are to be expected in the tidal torques scheme. Studies of interacting spherical systems very related to ours have been done using the Newtonian theory of gravity, including a number of topics: mergings (White 1978, 1979), mixing processes (White 1980), simulation of sinking satellites (White 1983a), and mass and energy lost in tidal interactions (Aguilar & White 1985), among others. However, we made our calculations within the framework of scalar-tensor theories, in the Newtonian limit, to investigate the influence of massive scalar fields on the dynamics.

This paper is organized as follows: In section 2 we present the Newtonian approximation of a typical scalar field theory. In section 3, we present our models of protogalaxies, the initial conditions, and the results. The conclusions are in section 4.

2 Scalar Fields and the Newtonian Approximation

We consider a typical scalar field theory given by the following Lagrangian

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

from which we get the gravity equations,

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi}{\phi} T_{\mu\nu} + V \frac{\omega}{\phi^2} \partial_\mu \phi \partial_\nu \phi - \frac{1}{2} \frac{\omega}{\phi} (\partial\phi)^2 g_{\mu\nu} + \frac{\phi_{\mu\nu}}{\phi} - \frac{g_{\mu\nu}}{\phi} \Box \phi$$

(2)
and the scalar field equation

\[
\Box \phi + \frac{\phi V' - 2V}{3 + 2\omega} = \frac{1}{3 + 2\omega} \left[ 8\pi T - \omega' (\partial \phi)^2 \right]
\]  

(3)

We expect to have nowadays small deviations of the scalar fields around the background defined here as \( \langle \phi \rangle = 1 \). If we define \( \bar{\phi} = \phi - 1 \) the Newtonian approximation gives (Helbig 1991)

\[
R_{00} = \frac{1}{2} \nabla^2 h_{00} = 4\pi \rho - \frac{1}{2} \nabla^2 \bar{\phi}
\]

(4)

\[
\nabla^2 \bar{\phi} - m^2 \bar{\phi} = -8\pi \alpha \rho
\]

(5)

where we have done

\[
\frac{\phi V' - 2V}{3 + 2\omega} = m^2 \bar{\phi} - m^2 k \bar{\phi}^2 + \ldots
\]

and \( \alpha = 1/(3 + 2\omega) \).

The solution of these equations is

\[
\bar{\phi} = 2\alpha u_\lambda
\]

\[
h_{00} = -2u - 2\alpha u_\lambda
\]

(6)

where

\[
u = \sum_a \frac{m_a}{|r - r_a|}
\]

\[
u_\lambda = \sum_a \frac{m_a}{|r - r_a|} \exp \left[ -|r - r_a|/\lambda \right]
\]

(7)

\( \lambda = 1/m \), where \( m \) is the mass given through the potential. This mass can have a variety of values depending on the particular particle physics model. The potential \( u \) is the Newtonian part and \( u_\lambda \) is the dark matter contribution which is of Yukawa type. The total force on a particle of mass \( m_i \) is

\[
\sum F = -\frac{1}{2} \nabla h_{00} = m_i a
\]

(8)
3 Protogalactic Cloud Models and Results

Original protogalaxies could have very irregular forms, but we use as a first approximation spherical clouds for simplicity, and because this form seems to resemble the global shape of both visible and dark matter of many galaxies, i.e., taking into account their spherical halos (Ostriker & Peebles 1973, White 1983b). The initial clouds are in polytropic equilibrium with small internal velocities, compared to what they would need to be in dynamical, gravitational equilibrium. This feature avoids a large initial spin, in accordance with the fact that there were no primordial rotational motions in the universe (Ozernoy & Chernin 1968; Parijskij 1973; Boynton & Partridge 1973; Peebles & Silk 1990). Then, the clouds are sent to approach each other, and only after their gravitational interaction takes place, spin will be gained.

For the simulations, each protogalaxy is constructed using the Plummer model given by the potential-density pair (Aarseth et al 1974),

\[ \Phi_P(r) = -\frac{GM}{\sqrt{r^2 + b^2}}, \quad \rho_P(r) = \left(\frac{3M}{4\pi b^3}\right) \left(1 + \frac{r^2}{b^2}\right)^{-5/2} \]

where \( G \) is the gravitational constant, \( M \) is the total mass and \( b \) is a parameter which determines the dimensions of the cloud. Particle velocities are chosen everywhere isotropic which gives a system initially in steady state. The total energy of the cloud is \( E = -(3\pi/64)GM^2b^{-1} \). We are using units in which \( G = M = -4E = 1 \).

We take two identical 3-D clouds consisting of \( N = 2^{11} \) particles. The initial separation between the clouds is 10, and the velocity of the center of masses are \( V_1 = (0.1, 0.1, 0) \) and \( V_2 = (-0.2, 0.4, 0) \) in our units. The initial velocities are given so that the kinetic energy is a fraction of the potential energy and we consider a range that is consistent with the observed velocities of galaxies in clusters that goes from 50 km/s up to about 1000 km/s. For the present investigation we consider that the protogalaxies moves initially in the plane \((x, y)\), and the angle of both protogalaxies is the same. More general initial conditions will be considered in a future communication.

A three-dimensional hydrodynamic code based on the TREESPH algorithm formulated by Hernquist & Katz (1989) was used for the computations of this paper. The code combines the method of SPH, developed by Lucy (1977) and Gingold & Monaghan (1977), with the hierarchical tree algorithm of Hernquist (1987) for the calculation of the gravitational acceleration forces.
Figure 1: Evolution of the angular momentum without scalar field and with scalar field for different values of $\lambda$. 
The SPH method is a grid-free Lagrangian scheme in which the physical properties of the fluid are determined from the properties of a finite number of particles. In order to reduce the statistical fluctuations resulting from representing a fluid continuum by a finite set of particles, a smoothing procedure is employed in which the mean value of a field quantity is estimated from its local values by kernel interpolation. Thus, the evolution of particle $i$ is determined by solving Euler’s equation

$$\frac{dr_i}{dt} \equiv v_i$$

$$\frac{dv_i}{dt} = -\frac{1}{\rho} \nabla p_i - \frac{1}{2} \nabla (h_{00})_i + A_{\text{visc},i},$$

where $p_i$ and $A_{\text{visc},i}$ denote, respectively, the gas pressure and the artificial viscous acceleration associated with particle $i$. This quantities are introduced because we are considering that the protogalaxies are gaseous. The code was modified (Rodríguez-Meza 2000) to include the effect of the scalar field, through the term $h_{00}$ given by Eq. (6).

The simulation of the interaction of two protogalactic models starts with the clouds separated by a distance of 10 and on the $x$-axis. The selected separation is large enough to ensure that tidal effects are important but small enough that the calculation is possible in a reasonable computing time. Each particle in the initial steady state clouds is given an additional velocity ($V_1$ or $V_2$, corresponding to cloud 1 or 2) so that its magnitude is much bigger than the internal velocities they have at the equilibrium described above. In this way, initial clouds are almost spinless, and the given velocities $V_1$, $V_2$ imply kinetic energies associated with each cloud. The evolution of the intrinsic angular momentum ($J/M$) with respect to the center of mass of each cloud is shown in Fig. 1. Continuous lines indicate cloud 1 and dashed lines cloud 2. The first plot is without scalar field, the other plots consider values of $\lambda$ of $b/16$, $b/32$, and $b/64$, respectively. We observe that the intrinsic angular momenta start from their initial values to a constant mean value approximately of 0.75 which in the cgs units is of the order of $10^{30}$ cm$^2$/s. This transient stage is slower without scalar field than the ones which consider scalar field. The faster transient occurs when $\lambda$ is bigger. In Fig. 2 we show plots of phase space $v_r$ versus $r$ of the whole system and for the same cases as Fig. 1. The scalar field extends the phase space in the $v_r$ direction.
Figure 2: Phase space $v_r$ versus $r$ of the combined system after the transient stage without scalar field and with scalar field for different values of $\lambda$. 
4 Conclusions

We have made other computations varying the kinetic energy from 4 to 1/16 times the potential energy. For large values of the kinetic energy the deflection is small, but for small values there is a considerable deflection, and in some cases we got almost a head-on collision. This is consistent with the known fact that the merging probability in an encounter of two clouds is enhanced significantly when the encounter takes place at relatively low speed (see for instance Makino & Hut 1997). We found that only close encounters and mergings permit the original spinless clouds to gain rotational velocities as is observed in typical galaxies nowadays. Similar studies have being done (Namboodiri & Kochhar 1991) considering point mass perturbers. In our approach the perturber is itself a protogalaxy and therefore the dynamics is more complicate, especially in close encounters. We have also found that the transient time to spin up the clouds depends on the scalar field. The transient stage is faster than the one without scalar field. When the scalar field is included faster transients occur for bigger values of \( \lambda \). The phase space \( v_r \) versus \( r \) of the combined system is also more extended in the \( v_r \) direction with scalar field than the one without scalar field.

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