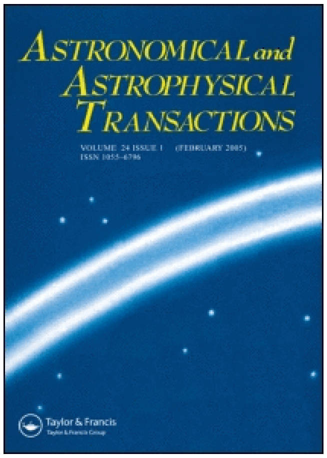

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THE COLLAPSE OF A SPHERICAL DENSITY PERTURBATION IN THE PRESENCE OF DYNAMICAL FRICTION

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We considered the collapse of a shell of baryonic matter falling into the central regions of a cluster of galaxies taking into account the presence of the substructure, inducing dynamical friction. In this context, we solve numerically the equation of motion of the shell of baryonic matter and we calculate the evolution of the expansion parameter, $a(t)$, of the perturbation using a coefficient of dynamical friction, η. The effect of the dynamical friction is to slow down the collapse, producing a variation of the parameter of expansion of the shell. The effect increases with increasing η.

KEY WORDS Theory of cosmology, formation of galaxies

1 INTRODUCTION

Accretion and secondary infall of matter into a cluster of galaxies has been studied by many authors (Gunn and Gott, 1972; Gunn 1977; Hoffmann and Shaman 1985) with particular interest in the prediction of the density profiles of the collapsed objects and to the calculation of the velocity fields.

Observational evidence for secondary infall in the outskirts of a cluster of galaxies has been reported by Regös and Geller (1989) and Briel *et al.* (1991). In the spherical accretion model introduced by Hoyle in 1966 and applied to clusters of galaxies by Gunn and Gott (1972), the matter around the core of the perturbation is a homogeneous fluid with zero pressure; if the density inside the perturbation is greater than the critical density it is bound and expands to a maximum radius r_m:

$$r_m = \frac{r_i}{\bar{\delta}} \tag{1}$$

where r_i is the initial radius and $\bar{\delta}$ is the overdensity in the radius r, and it collapses in a time:

$$T_{c0}/2 = \frac{\pi}{H_i}\frac{(1+\bar{\delta})}{\bar{\delta}^{3/2}} \tag{2}$$

where H_i is the Hubble parameter at the inital time t_i. The Gunn and Gott model neglects: (a) tidal interaction of the perturbation with the neighbouring perturbation; (b) the substructure existing in the outskirts of galaxies and in the background. The effect of the tidal field and that of the substructure on the collapse of the perturbation are similar: they delay the collapse.

In the following we shall show how the unbound substructures influence the collapse of the perturbation.

The substructure acts as a source of stochastic fluctuations in the gravitational field of the protostructure inducing dynamical friction (AC) and eventually produces a modification of the motion of shells of matter in a density perturbation. The galaxies inside a shell of matter are subjected to the stochastic gravitational field produced by the substructure and their motion undergoes a preferential deceleration in the direction of motion. In particular, dynamical friction produces a delaying effect in the collapse of the regions of low density ($\bar{\delta} \simeq 0.01$) inside the perturbation (AC). The final result is that Gunn and Gott's model is inadequate to describe the collapse of a spherical perturbation and it requires revision.

To this end we used the modified equation of motion of a shell of baryonic matter in galaxies and substructure given by AC, in which is introduced a frictional force that takes into account dynamical friction effects (we study only the component of the dynamical friction due at the galaxies belonging to the shell and to the substructure not bound gravitationally to the shell) and we solved it by numerical integration.

In this paper we show: (a) how the expansion parameter, $a(t)$, of the shell is changed by the presence of substructure friction; (b) the changes produced by dynamical friction on the collapse time of the perturbation.

2 MODIFICATION OF THE EXPANSION PARAMETER OF A SHELL

The equation of motion of a shell of baryonic matter around a maximum of the density field, neglecting tidal interactions and substructure, can be expressed in the form:

$$\frac{d^2r}{dt^2} = -\frac{GM}{r^2(t)} \tag{3}$$

(Preebles 1980, equation 19.9), where M is the mass enclosed in the proper radius $r(t)$. Using the Gunn and Gott notation the proper radius can be written as:

$$r(r_i, t) = a(r_i, t) r_i \tag{4}$$

where r_i is the initial radius and $a(r_i, t)$ is the expansion parameter of the shell. At the initial time t_i the initial condition is given by

$$a(r_i, t_i) = 1. \tag{5}$$

In the presence of the substructure it is necessary to modify the equation of motion equation (3) because the graininess of the mass distribution in the system induces dynamical friction that finally introduces a frictional force term to equation (3).

In a material system the gravitational field can be decomposed into an average field, $\mathbf{F}_0(r)$, generated from the smoothed-out distribution of mass, and a stochastic component, $\mathbf{F}_{\rm stoch}(r)$, generated from the fluctuations in the number of neighbouring particles. The stochastic component of the gravitational field is specified by assigning a probability density $W(\mathbf{F})$ (Chandrasekhar and von Neumann, 1942). In an infinite homogeneous unclustered system $W(\mathbf{F})$ is given by the Holtsmark distribution (Chandrasekhar and von Neumann, 1942) while in inhomogeneous and clustered systems $W(\mathbf{F})$ is given by Kandrup (1980) and Antouccio and Barandela (1992), respectively. The stochastic force, $\mathbf{F}_{\rm stoch}$, in a self-gravitating system modifies the motion of particles as is done by a frictional force. In fact a particle moving faster than its neighbours produces a deflection of their orbits in such a way that the average density is greater in the direction opposite to that of the motion causing a slowing down in its motion. The modified equation of motion of a shell can be written in the form:

$$\frac{d^2\mathbf{r}}{dt^2} = -\frac{GM}{r^2(t)} - \eta\mathbf{v} \tag{6}$$

(Langevin, 1908; Saslaw, 1985; Kandrup 1980) where η is the coefficient of dynamical friction. Supposing that there are no correlations among random force and their derivatives we have:

$$\eta = \frac{\int d^3F W(F) F^2 T(E)}{2\langle v^2\rangle} \tag{7}$$

(Kandrup, 1980) where $T(F)$ is the average duration of a random force impulse, $W(F)$ is the probability distribution of stochastic force that for a clustered system is given by Antonuccio and Barandela (1992). Equation (6) in terms of $a(r_i,t)$ and

$$\rho(r_i,t) = \frac{3M}{4\pi a^3(r_i,t) r_i^3} = \frac{\rho(r_i,t_i)}{a^3(r_i,t_i)} = \rho_{ci}(1+\bar{\delta}_i) \tag{8}$$

can be written as:

$$\frac{d^2a}{dt} = -\frac{4\pi G\rho_{ci}(1+\bar{\delta}_i)}{a^2(t)} - \eta\frac{da}{dt} \tag{9}$$

where ρ_{ci} is the background density at a time t_i and $\bar{\delta}_i$ is the overdensity within r_i. Using the parameter $r = t/T_{c0}$, equation (9) may be written in the form:

$$\frac{d^2a}{d\tau^2} = -\frac{4\pi G\rho_{ci}(1+\bar{\delta}_i)}{a^2(t)}T_{c0}^2 - \eta T_{c0}\frac{da}{d\tau}. \tag{10}$$

Equation (10) is obtained by remembering that the probability density $W(F)$ depends linearly on the correlation function (AC). Referring to the calculation of η, given by AC and using equation (10) we obtained the time evolution of the expansion parameter, $a(\tau)$, of the shell of baryonic matter making up the galaxies and substructure. Equation (10) can be solved by looking for an asymptotic expansion as made by AC or numerically. In the quoted paper they gave only an expression for the collapse time T_c taking account of dynamical friction. We solved equation (10)

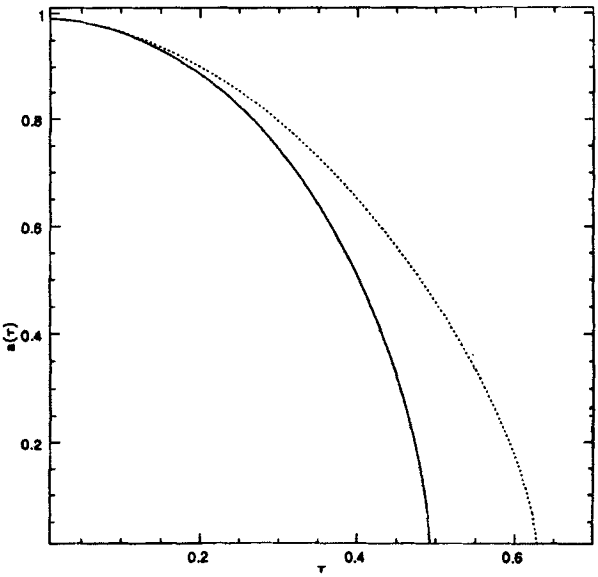

Figure 1 Temporal evolution of the expansion parameter of a shell of baryonic matter. The solid line is $a(\tau)$ when dynamical friction is absent while the dotted line represent the same when it is taken into account. We assume a cluster radius of $R_{\rm cl} = 5h^{-1}$ Mpc, and central overdensity $\bar{\delta} = 0.01$.

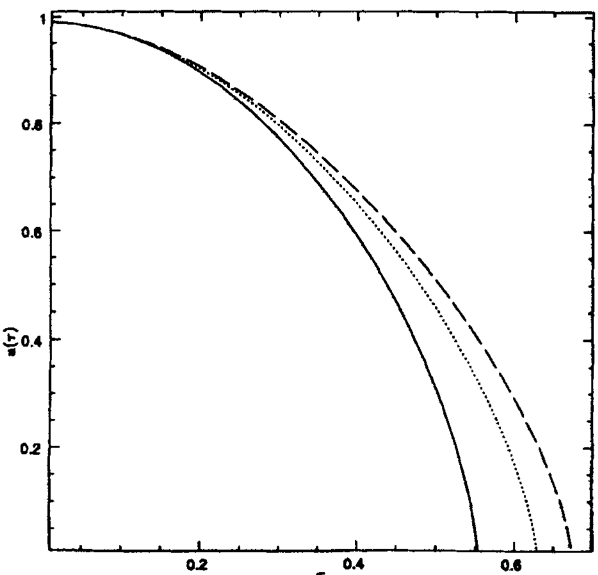

Figure 2 Temporal evolution of the expansion parameter $a(\tau)$ of a shell of baryonic matter for different values of η. The solid line is for η_1, the dotted line is for η_2 and the dashed line is for η_3 with $\eta_1 \le \eta_2 \le \eta_3$. We assume a cluster radius of $R_{\rm cl} = 5h^{-1}$ Mpc, and a central overdensity $\bar{\delta} = 0.01$.

numerically using a Runge–Kutta integrator of fourth order. We studied the motion of a shell of low density, $\bar{\delta} = 0.01$, typical of a perturbation present in the outskirts of a cluster of galaxies. We chose the initial conditions remembering that at the maximum of the expansion the initial velocity is zero. In Figure 1 we show the expansion parameter $a(\tau)$ versus $\tau = t/T_{c0}$, both when the dynamical friction is taken into account and when it is absent. Dynamical friction slows down the collapse of the shell of baryonic matter. In Figure 2, we report the same parameter $a(\tau)$ for different values of η, and you can see that the effect of slowing down of the collapse increases with increasing η.

3. CONCLUSIONS

In this paper we show how the parameter of expansion, $a(\tau)$, of a shell of baryonic matter making up the galaxies and substructure of a protocluster changes when the dynamical friction is taken into account. We showed that the expansion parameter decreases less steeply in the presence of dynamical friction, and we show how the effect grows with increasing η (see Figure 2).

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