The local effect of Dark Energy on the evolution of galaxy clusters: the formation of massive structures in the cluster centre

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Abstract

In this contribution we discuss how the centres of galaxy clusters evolve in time, showing the results of a series of direct N-body modelling at high resolution. In particular, we followed the evolution of a galaxy cluster with a mass of around 10^{14} M$_\odot$ in four different configurations: 1) isolated cluster; 2) cluster subjected to the action of Dark Energy; 3) cluster composed of galaxies and gas; 4) cluster composed of galaxies and gas subjected to the action of Dark Energy. The dynamical evolution of the system leads in all the cases to the formation of dense and massive substructures in the cluster centre, whose properties depend slightly on the kind of environment in which the cluster evolve. Indeed, these sub-structures form in consequence of a series of collisions and merging among the galaxies that move in the innermost region of the cluster under the action of the dynamical friction. In our contribution, we investigate how the structural properties of the merging product depends on the main characteristics of those galaxies that contributed to its formation and, moreover, to the effects induced by the environment in which the cluster evolves.

Introduction

Galaxy clusters (GCs) are the biggest bounded systems of the Universe, with masses up to 10^{15}M$_\odot$. A number of papers have recently proposed that these systems may hidden signatures of the antigravitational action of the dark energy (DE)[1]. Indeed, observations of the Virgo cluster have suggested that those galaxies travelling in an outer region of the cluster are flowing away following the so-called Hubble flow[2,3]. Using direct N-body simulations, we modelled the dynamical evolution of a GC under the action of DE[4], in order to understand whether the antigravity term in the equation of motion of each particle may play a significant role in shaping the structure of the GC outermost region. On the other hand, we investigated also the role of orbital decay and merging of those galaxies moving in the innermost region of the cluster, aiming to find significant differences in systems in which the total force acting on each particle is determined (or not) by the DE antigravity term. We found that the dynamical action of DE, coupled with a potential well associated with a gaseous component, seems to facilitate the formation of a central structure with a mass nearly 0.1 times the total cluster mass.

ID sim	DE	Gas	Gravity
MM1	✓		✓
MM2	✓	✓	✓
MM3		✓	✓
MM4			✓

Tab. 1: acceleration terms considered in solving the equation of motion of particles in each model.

Numerical Simulations

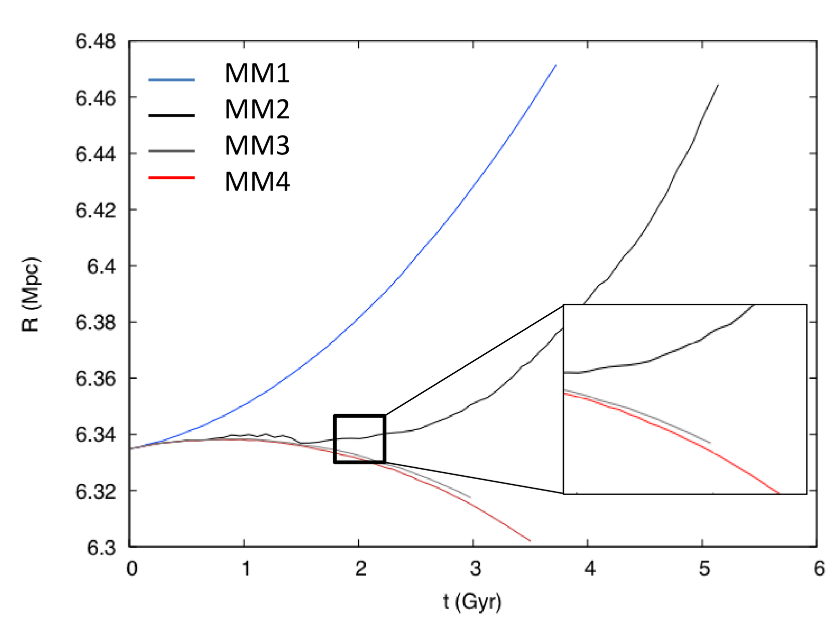

Fig. 1: Radial distance to the cluster centre as a function of the time for the same galaxy in the four simulation performed. It is evident that in simulations in which $F_{DE} \neq 0$ the galaxy flows away from the cluster.

We modelled the dynamical evolution of a GC composed of 241 galaxies using a modified version of the direct N-body code HiGPUs[5], in which each particle moves according to the equation of motion:

$$\ddot{\vec{r}}_i = \sum_j \frac{m_i m_j}{r_{ij}^2}\vec{r}_{ij} + \vec{F}_{DE} + \vec{F}_{gas},$$

where $\vec{F}_{DE}$ represents the force arising from DE, according to the ΛCDM-model:

$$\rho_{DE}(r) = \frac{\Lambda c^2}{8\pi G},$$

and $\vec{F}_{gas}$ represents the force arising from a gaseous component, modelled according to the so-called β-profile[6]:

$$\rho_{gas}(r) = \rho_{0gas}\left[1+\left(\frac{r}{r_c}\right)^2\right]^{3\beta/2}.$$

In order to highlight the different role played by each component, we switched on/off alternatively the DE or gaseous term, as indicated in Table 1.

In our simulations, each galaxy is composed of more than 10^4 particles, for a total number of particles exceedings 10^6. This allow us to have a clean view of the dynamics of galaxies, despite we cannot account for radiative mechanisms. In order to reduce this problem, the gas component has a mass smaller than the 5% of the total cluster mass, and therefore its radiative contribution to the evolution of the cluster can be substantially neglected[7]. Galaxies within the cluster are distributed according to a β- profile with $3\beta/2 = -1$. Such a choice corresponds to the so-called King-like profiles[8]. Galaxy masses are sampled in the range 9×10^{10}M$_\odot$ and 10^{12}M$_\odot$ according to the following IMF[9]:

$$f\left(M_{gal}\right) \propto M^{-1}.$$

Galaxies are characterized by Dehnen density profiles[10]:

$$\rho_D(r) = \rho_{0D}\left(\frac{r}{a}\right)^{-\gamma}\left[1+\frac{r}{a}\right]^{-4+\gamma},$$

with inner slopes in the range $0.2 < \gamma < 1.74$.

Our GC model's main parameters are summarized in Table 2.

M_{gal} ($10^{13}M_\odot$)	r_c (Mpc)	r_{tot} (Mpc)	r_{ZGR} (Mpc)
9.2	0.1	12	4.8
N_{gal}	$m_{g,min}$ ($10^{10}M_\odot$)	$m_{g,max}$ ($10^{10}M_\odot$)	
10^6	9	100	

Tab. 2: Main parameters of our GC model.

We found that DE affects significantly the motion of those galaxies traversing the outer region of the cluster. In particular, galaxies moving beyond the so-called Zero-Gravity Radius, which is the radius within gravity overcomes antigravity, flow away at increasing velocities. For instance, Figure 1 shows the time evolution of the radial distance to the galactic centre for galaxy no. 87 in the four simulation performed. It is evident that in the cases in which DE is turn on the galaxy escape from the cluster. Further details on this results will be given by Dr. M. Donnari during her talk on Wednesday 9th in the DE session.

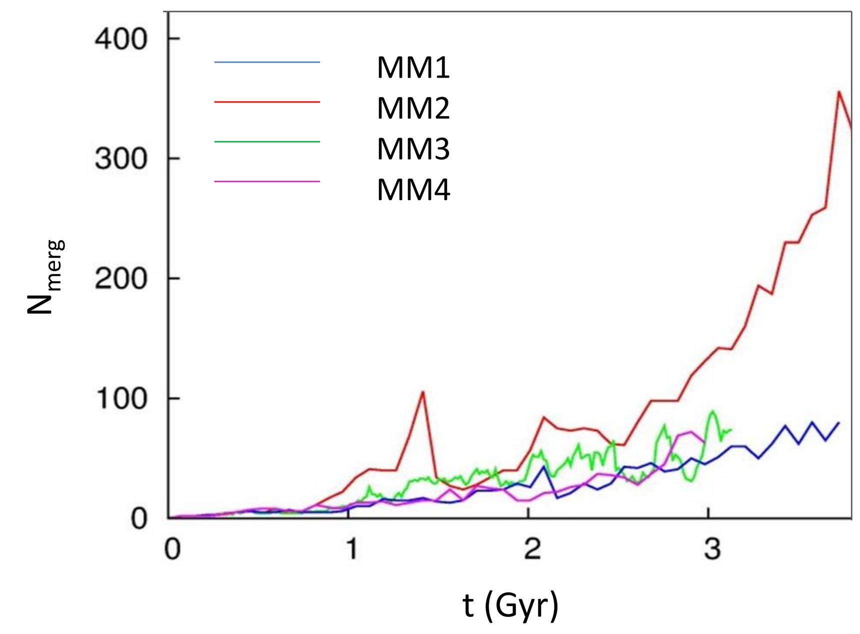

Fig. 2: Number of merging as a function of the time for the four simulations performed.

Results

Concerning the dynamical evolution of the cluster nucleus, we followed the orbits of the central galaxies. Indeed, these galaxies are efficiently affected by dynamical friction, which drags them toward the cluster centre.

Surprisingly, the combined action of DE and gas seems to facilitate collisions among galaxies. Indeed, the number of merging is much higher in simulation MM2, in which DE and gas potentials are switched on (see Figure 2).

Our results show that a sequence of 29 merging and collisions occur over a time-scale t ~ 5 Gyr driving the formation of a huge spheroidal structure. The central merging product is composed of 15 galaxies and has a total mass of $M = 10^{13}$M$_\odot$ and a central velocity dispersion $\sigma \simeq 800\ km\ s^{-1}$.

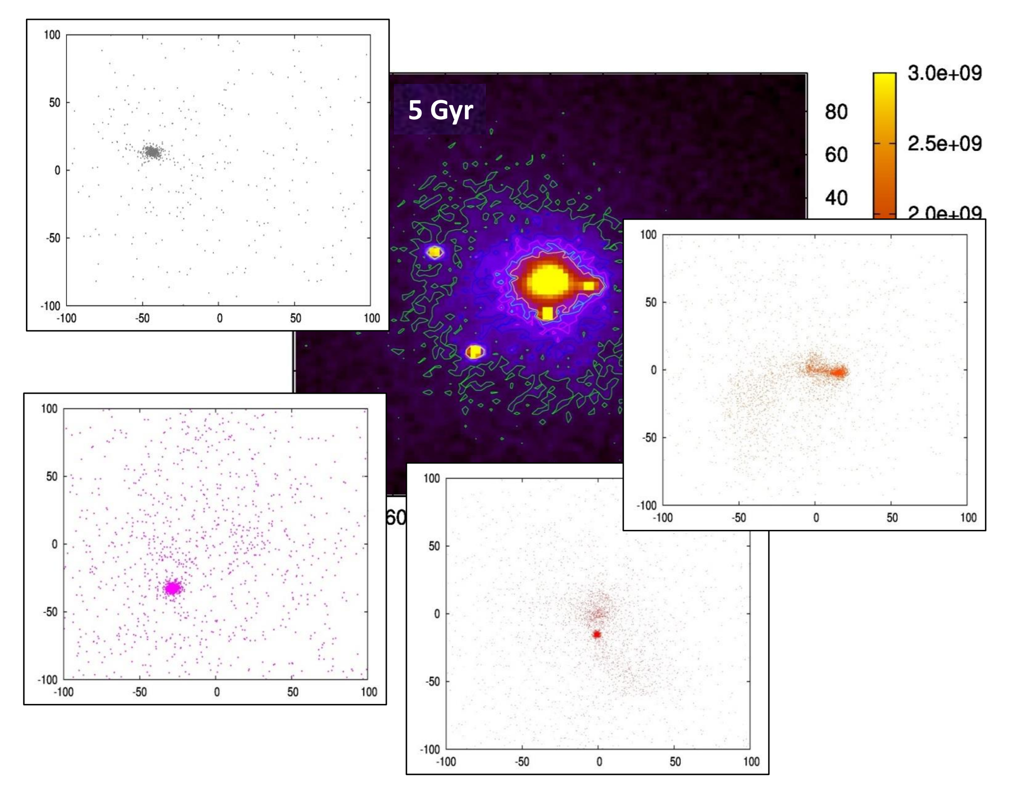

Fig. 3: Surface density map of the largest merging product formed in all the simulations. The bright spots located around the central spot are tidal debris of galaxies that moves around the GC centre, as indicated in the four panels.

Its density profile is well fitted by a broken power-law with inner slope $\gamma = 0.5$ and scale radius $a = 14$ kpc. The correspondent half-light radius of this structure is $r_{eff} = 42$ kpc.

Figure 2 shows a surface density map of this structure in configuration MM2. The brights spots distributed around its centre are debris of tidally disrupted galaxies, which are represented in the four related panels of the figure.

The newly born structure has a total mass ~ 11% times the total mass of the cluster, in good agreement with observational estimates of masses for the central elliptical galaxies observed in almost all the observed GCs.

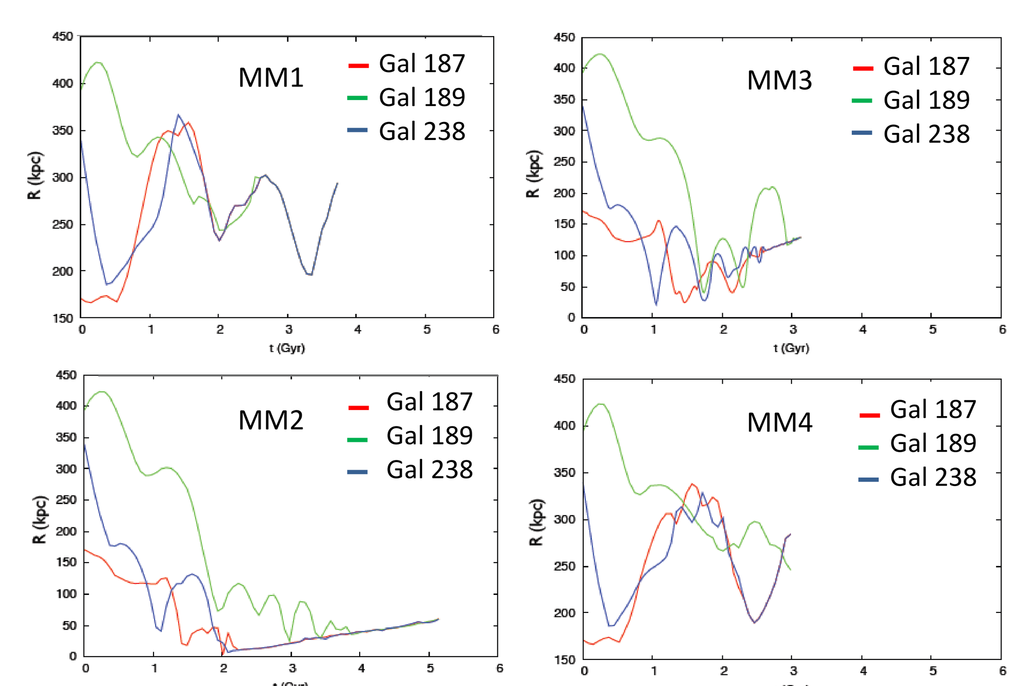

Fig. 4: Radial distance to the cluster centre for 3 galaxies in the four simulations performed as a function of the time. In all the cases, the galaxies collide and merge leading to the formation of a new structure.

The four panels in Figure 4 show the time time evolution of the distance to the GC centre for three galaxies (no. 187, 189 and 238) in all the simulations performed. It is interesting to highlight that in configuration MM1, in which DE and gas are switched on, the three galaxies merge within 2 Gyr, while these process is significantly delayed in all the other cases studied. Indeed, in configurations MM2-3-4 the formation of a structure occurs on a time-scale greater than $3 - 3.5$ Gyr. A deeper analysis on all the significant merging that occur in our simulations seem to suggest that the combined action of the repulsive term (DE) and the attractive term related to the gas allows a faster merging process.

Conclusions and Future Developments

- ✓ In order to investigate the role of DE in shaping the inner and outer region of GCs, we simulated the evolution of a GC composed of 241 galaxies in four different configurations, using a direct N-body code;
- ✓ We found that DE plays a significant role in determining the motion of those galaxies moving in the outer region of the GC, leading some galaxies to flow away from the cluster centre with an increasing velocity;
- ✓ We found that the velocity at which galaxies flows away is a linear function of the distance from the GC centre;
- ✓ Concerning the GC nucleus, we found that a series of collisions and merging among 16-20 galaxies lead to the formation of a huge galaxy with a mass 10% of the total mass of the cluster, surrounded by several satellite galaxies that are debris of heavier progenitor tidally stripped by the cluster nucleus;
- ✓ Our results seem to suggest that the combined action of DE and gas facilitiate collisions and merging among galaxies, although this analysis is currently under deeper investigation.

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