Exploring Mergers of Galaxy Clusters in Cosmological Context

Susana Planelles and Vicent Quilis

Abstract We present results of an Eulerian adaptive mesh refinement (AMR) hydrodynamical and N-body simulation in a ΛCDM cosmology. The simulation incorporates common cooling and heating processes, a phenomenological description of the star formation and supernovae feedback. A specific halo finder has been designed and applied in order to extract a sample of galaxy clusters directly obtained from the simulation without considering any resimulating scheme. We have studied the evolutionary history of the cluster halos, and classified them in three categories depending on the merger events they have undergone. We pay special attention to discuss the role of merger events as a source of feedback and reheating.

1 Introduction

Galaxy clusters are extremely valuable laboratories where to explore the connection between cosmological scales and the formation and evolution of galaxies.

The simplest model explaining the properties of the ICM is the self-similar model [3], which assumes that gravity is the only responsible force determining the evolution of the ICM. The discrepancies detected between the self-similar model and the observations have motivated the idea that some important physics, basically related with the baryonic component, is missing in the model. Some of this non-gravitational processes have been included in simulations trying to solve the similarity breaking: preheating (e.g., [7]) and radiative cooling (e.g., [8]). More sophis-

Susana Planelles
Departament d'Astronomia i Astrofísica, Universitat de València, 46100 - Burjassot (Valencia), Spain, e-mail: susana.planelles@uv.es

Vicent Quilis
Departament d'Astronomia i Astrofísica, Universitat de València, 46100 - Burjassot (Valencia), Spain, e-mail: vicent.quilis@uv.es

ticated approaches coupling the feedback with cooling and star formation have been carried out by [4] among others.

Merger events can also be an important source of feedback in galaxy clusters. They can produce shocks and compression waves in the halos and eventually release part of the energy associated to the collision as thermal energy in the final system [6]. Turbulence and mixing will play a crucial role in how this energy is mixed and released in the ICM of the final halo after the merger.

In this contribution, we explore the role of galaxy cluster mergers as a source of feedback and reheating, in a complete general cosmological framework. We would like to stress that we do not wish to assume any symmetry or idealized clusters. In the same manner, we want to look at merger events produced by the hierarchical evolution, and not to simplified collisions fixed by hand. In order to do so, we have carried out a hydrodynamical simulation of a moderate size box in which we have identified and followed the evolution of the different galaxy cluster halos. Once the evolutionary history of the halos is known, we have classified them in three broad categories depending on the features of the merger events in which they have been involved. We will discuss their effects on cluster properties. It must be stressed that these merger events are not idealised but the ones naturally happening in the building up of the galaxy clusters.

2 Simulation Details and Cluster Identification

We have carried out an N-body/hydrodynamical simulation of a box of side length $100\,h^{-1}\,Mpc$, performed with the Eulerian AMR cosmological code MASCLET [10]. The simulation assumes a concordance ΛCMD cosmological model ($\Omega_m = 0.25$; $\Omega_\Lambda = 0.75$; $\Omega_b = 0.045$; $h = 0.73$; $n_s = 1$; $\sigma_8 = 0.8$). The computational domain was discretized with 512^3 cubical cells and it was used a maximum of seven levels of refinement (peak spatial resolution of $3\,h^{-1}\,kpc$). For the dark matter, we consider two particles species being the best mass resolution $5.75 \times 10^8\,h^{-1}\,M_\odot$, equivalent to distribute 512^3 particles in the whole box. The simulation includes processes of cooling and heating for primordial gas, and a phenomenological star formation treatment with supernovae feedback.

In order to identify the clusters in the simulation, we have developed a halo finder specially suited for the features of the cosmological code MASCLET. We have used an identification method based on the original idea of the spherical over-density (SO) method. The basic concept of this technique is to identify spherical regions with an average density above a certain threshold, which can be fixed according with the spherical top-hat collapse. The SO method implies oversimplifications which could lead to somehow artificial results which deserve a careful treatment. Nevertheless, the practical implementation of our halo finder has several steps designed to improve the performance of the SO method and to get rid of the possible drawbacks. One of the main advantages of our method is that the structure of nested grids created by the AMR scheme already follows the density peaks, and therefore, densities are already calculated by the cosmological code. Other important point, inherent to the structure of the AMR scheme used, is that no linking length is needed. In addition, the process of halo finding can be performed, independently, at each level of refinement of the simulation. Then, in a natural way, our halo finder can trace halos-in-halos and obtain a hierarchy of nested halos.

The different progenitors of the halos are identified by following all particles belonging to a given halo backwards in time until the first progenitor of a certain halo is found. This method allows us, not only to know all the progenitors of each halo, but the amount of mass received from each one of its ancestors.

3 Results

In our simulation, we have identified more than three hundred galaxy clusters and groups spanning a range of masses from $1.0 \times 10^{13} M_{\odot}$ to $2.0 \times 10^{15} M_{\odot}$. We have constructed their evolutionary histories and, based on their merging history, we have classified them into three categories: relaxed (or with no relevant mergers), with minor mergers and with major mergers. The galaxy clusters identified as relaxed, basically, grow by smooth accretion, whereas those having mergers have suffered some violent event at certain epoch of their evolution.

We classify the clusters with mergers depending on the mass ratio of the halos involved in the collision. Thus, if we consider the mass of the most (less) massive halo, m_2 (m_1), involved in the merger, we have the following classification:

- Major mergers. Those systems where the mass ratio $m_2 : m_1$ is smaller than $3:1$.
- Minor mergers. Those systems where the mass ratio is $3:1 < m_2 : m_1 < 10:1$.
- Relaxed halos. Those systems which have suffered mergers with very small halos, $10:1 < m_2 : m_1$ or smooth accretion.

3.1 Average Radial Profiles

We have picked up a sample which contains the sixteen most massive galaxy clusters in the computational box. The analysis presented in this work focus on those clusters. Concerning their merging classification, we have found five relaxed clusters, three have been categorised as clusters with minor mergers, and eight have been classified as major merger systems.

In order to analyse the main properties of the simulated galaxy clusters, we plot in Fig. 1 average radial profiles for several quantities. These profiles are centred at the centre of mass of each halo and run outwards from the centre to a distance slightly larger than the virial radius. The bins are equispaced in logarithmic scale with widths 0.1 dex. These profiles are computed by averaging all the profiles of the clusters of each class.

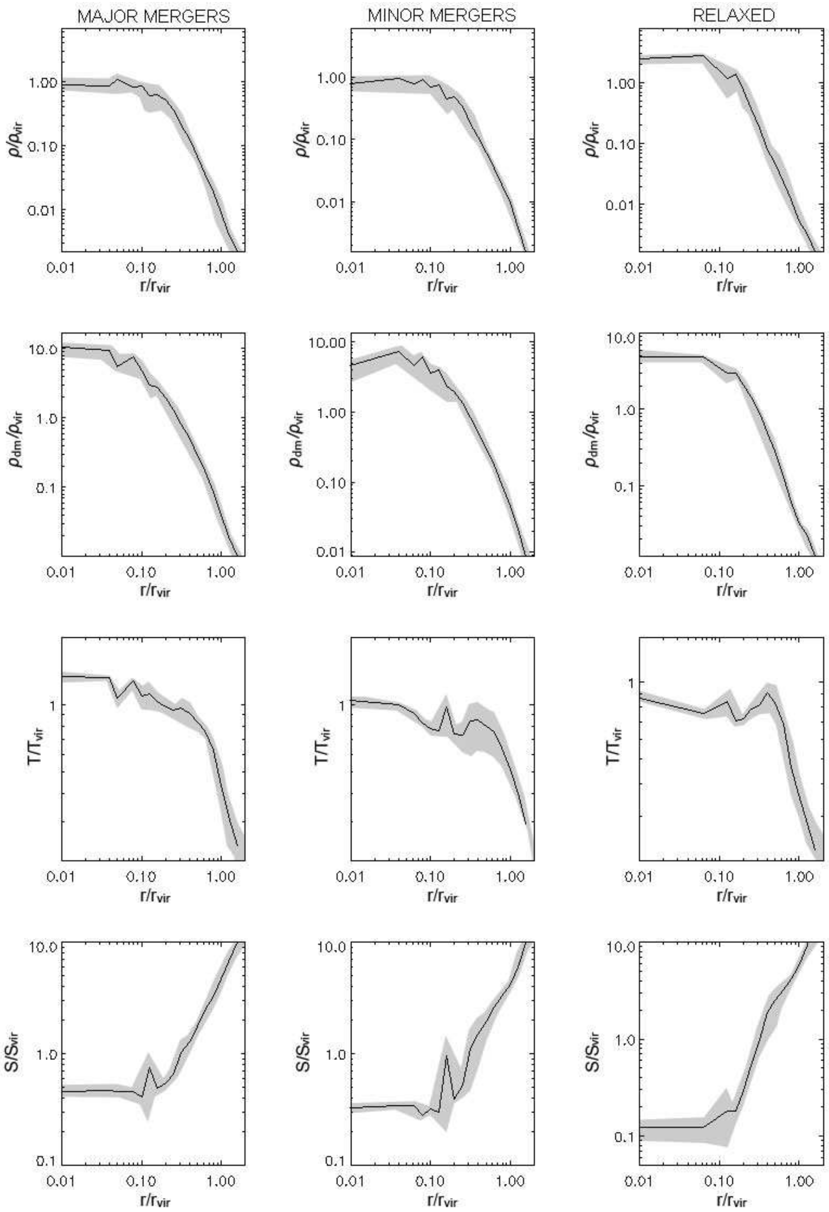

Fig. 1 Average radial profiles at $z = 0$ for all clusters belonging to each class: major mergers (left column), minor mergers (central column), and relaxed (right column). From top to bottom, the first and second rows display gas (ρ/ρ_{vir}) and dark matter (ρ_{dm}/ρ_{vir}) densities, respectively, the third row shows mass-weighted temperature (T/T_{vir}), and the fourth row represents entropy (S/S_{vir}). All profiles have been scaled by the mean value of the plotted quantities within the virial radius. Continuous lines show the average for all the individual profiles of each class of clusters. Shadowed regions represent one σ deviation. The radial coordinate is normalised to the virial radius.

A detailed analysis of Fig. 1 shows interesting differences among the three categories in which we have classified the different clusters. The comparison of gas and dark-matter density profiles do not show notable differences. Whereas for the gas density, the relaxed clusters exhibit a slightly higher density at the centre compared with the minor and major merger clusters, the behaviour for the dark matter is the opposite, having a higher density the major merger clusters. In any case, the profiles are, in all cases, consistent with the expected characteristics of density profiles for galaxy clusters.

Concerning the temperature profiles, there are no dramatic differences neither. All clusters show a central core with an almost constant temperature and a declining profile outwards. This result is compatible with observational data (e.g., [2]), and with the idea of a quite universal temperature profile for the galaxy clusters [5]. The major and minor merger cluster profiles have very similar central temperatures, although the isothermal core is larger for the major merger clusters. The relaxed clusters have a larger isothermal core with a slightly lower value of the temperature compared with the major and minor merger clusters.

More interesting is the analysis of the entropy profiles. In all cases, the clusters have entropy cores and profiles out of the core compatible with $S \propto r^{\alpha}$ with $\alpha \sim 1$ [1]. Moreover, the generic shape of the entropy profiles does not seem to depend systematically on the mass or temperature of the clusters, in agreement with observations [9]. The sizes of the cores are similar in the relaxed and minor merger clusters and slightly larger in the major merger ones. As it would be naively expected, the entropy floor in the relaxed clusters is lower than for the minor merger clusters, and this one is also lower than for the major merger clusters. Although the differences seem not to be dramatic, they are clearly visible in the mean profiles. These differences in the value of the entropy in the core, would be a clear consequence of the different evolutionary histories of each cluster.

3.2 Scaling Relations

The galaxy cluster sample studied in this contribution is focused on the most massive clusters of our simulation — the best numerically resolved. In the present subsection, and only for the study of the scaling relations, we have extended the previous sample by considering all clusters with a virial temperature equal or higher than 1 keV. Our results can be fitted by the following scaling relations: $L \propto T^{2.3}$, $M \propto T^{1.4}$, and $S \propto T^{0.9}$, where L, M, S and T represent the X-ray luminosity, the virial mass, the mean entropy and the virial temperature, respectively. These results are consistent with previous results, specially considering that it has not been introduced any other pre-heating or feedback mechanism, besides the one from the star formation and the so-called gravitational feedback (shock waves, mergers, etc).

In any case, even when the sample can be limited, we wish to stress that the individual properties of each of the most massive clusters are well defined.

4 Discussion and Conclusions

We have presented the results of a hydro and dark matter simulation of a moderate size volume of the Universe in the framework of a concordance cosmological model. The simulation, which includes radiative cooling, heating and cooling for a primordial gas, supernovae feedback and star formation, was carried out with the AMR Eulerian code MASCLET.

Our idea in the present work was to analyse the effects of galaxy cluster mergers as a source of feedback and reheating. In order to do so, we have extracted and followed the evolution of the galaxy cluster like halos in our simulation. These halos have been studied directly from the simulation and without any resimulating scheme. Therefore, mergers can be followed in a consistent way as they naturally occur in the evolution of the simulated volume of the Universe.

We have studied the evolutionary history of the cluster halos, and classified them in three categories (major merger, minor merger, and relaxed clusters) depending on the merger events they have undergone. In order to compare the main differences among the three classes and to study the role of mergers in the ICM properties, we have computed average radial density, entropy and mass-weighted temperature profiles for each group. The forms of the different profiles are basically the same for the three categories, indicating no substantial changes in the physics of clusters. However, there is a trend in the normalisation. The relaxed and minor merger clusters have similar value of all quantities, whereas the major merger clusters are slightly hotter and with higher entropy.

The role of mergers as source of feedback, transferring part of the gravitational energy to the thermal energy, is still a matter of debate and study. Mergers are crucial to understand galaxy cluster formation and galaxy formation scenarios as they influence directly in the ICM properties. Simulations with higher resolution and including more physical processes are needed in order to keep on quantifying the role of mergers in the hierarchical scenario of structure formation.

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References

1. Borgani S., Diaferio A., Dolag K., Schindler S., 2008, SSRv, 134, 379
2. De grandi S., Molendi S. , 2002, ApJ, 567, 163
3. Kaiser N., 1986, MNRAS, 222, 323
4. Kay S.T., Thomas P.A., Theuns T., 2003, MNRAS, 343, 608
5. Loken C., Norman M. L., Nelson E., et al , 2002, ApJ, 579, 571
6. McCarthy I.G., 2007, MNRAS, 376, 497
7. Navarro J.F., Frenk C.S., White S.D.M., 1995, MNRAS, 275, 720
8. Pearce F.R., Thomas P.A., Couchman H.M.P., Edge A.C., 2000, MNRAS, 317, 1029
9. Ponman T.J., Sanderson A.J.R., Finoguenov A., 2003, MNRAS, 343, 331

10. Quilis V., 2004, MNRAS, 352, 1426