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Cool cores and galaxy cluster mergers

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Abstract

We present the results of an Eulerian adaptive mesh refinement (AMR) hydrodynamical and N-body simulation in a ΛCDM cosmology carried out with the cosmological code MASCLET. The simulation incorporates common cooling and heating processes for primordial gas. The ASOHF halo finder has been 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 haloes, and classified them into three categories depending on the merger events they have undergone. We discuss the role of merger events as a source of feedback and reheating of the ICM, and specially, their effects on the existence of cool cores in galaxy clusters, as well as in the scaling relations.

1 Introduction

Galaxy clusters are crucial pieces in our understanding of the Universe since they let us 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 [4]. It 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 these non-gravitational processes have been included in simulations trying to solve the similarity breaking: preheating (e.g. [8]) and radiative cooling (e.g. [10]). More sophisticated approaches coupling the feedback with cooling and star formation have been carried out by [5] among others.

Merger events can also be an important source of feedback in galaxy clusters. They can produce shocks and compression waves in the haloes and eventually release part of the energy associated to the collision as thermal energy in the final system. 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 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 haloes. Once the evolutionary history of the haloes is known, we have classified them into three broad categories depending on the the merger events in which they have been involved. We will discuss their effects on cluster properties paying special attention to their effects on the existence of cool cores in galaxy clusters, as well as in the scaling relations.

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 [14]. The simulation assumes a concordance ΛCDM cosmological model ($\Omega_\mathrm{m} = 0.25$; $\Omega_\Lambda = 0.75$; $\Omega_\mathrm{b} = 0.045$; $h = 0.73$; $n_\mathrm{s} = 1$; $\sigma_8 = 0.8$). The computational domain was discretized with 512^3 cubical cells and it has a peak spatial resolution of $3\,h^{-1}\,\mathrm{kpc}$. For the dark matter, we consider two particles species being the best mass resolution $5.75 \times 10^8\,h^{-1}\,\mathrm{M}_\odot$. The simulation includes processes of cooling and heating for a primordial gas, and a phenomenological star formation treatment with supernovae feedback. For further details about the simulation and the obtained results we address the reader to [11].

In order to identify and characterize the clusters in the simulation, we have used the ASOHF halo finder [12] which makes use of an identification technique based on the original idea of the spherical over-density (SO) method.

3 Results

In our simulation, we have identified more than three hundred galaxy clusters and groups spanning a range of masses from $1.0 \times 10^{13}\,\mathrm{M}_\odot$ to $2.0 \times 10^{15}\,\mathrm{M}_\odot$. We have constructed their evolutionary histories and, based on their merging histories, we have classified them into three categories according to the mass ratio of the haloes involved in the collision. We have also taken into account the formation redshift of a cluster, z_for [7], since mergers occurring at a very early epoch would not have any important consequence on the present properties of the clusters. Therefore, taking into account z_for and the masses of the most (less) massive halo, m_2 (m_1), involved in the merger, we have classified the clusters into three categories: major mergers ($m_2 : m_1 < 3 : 1$), minor mergers ($3 : 1 < m_2 : m_1 < 10 : 1$) and relaxed haloes ($10 : 1 < m_2 : m_1$).

3.1 Cool core clusters

It is well known that galaxy clusters exhibit an important feature that allows to classify them into two separate populations: cool core (CC) and non cool core (NCC) clusters. Recently,

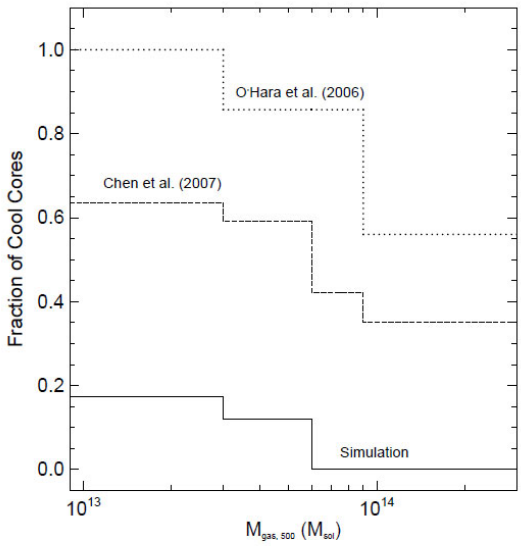

Figure 1: Fraction of CC clusters in our simulation vs. the gaseous mass of the clusters. The simulated clusters (continuous line) and the observed clusters from [2] (dashed line) and [9] (dotted line) are binned in five linearly equispaced bins.

[2] concluded that $\sim 46\%$ of the population observed in a sample with more than hundred clusters have CCs. The explanation for this dichotomy is not clear and it remains a matter of debate. By means of SPH simulations, [6] overestimate the number of CC clusters since almost all their clusters show the presence of CCs. However, [1], using an Eulerian AMR code, obtained an abundance of CC clusters at $z \sim 0$ of $\sim 16\%$. It is likely that feedback processes could be directly involved in the survival of CCs in clusters, but it is also possible that mergers could play an important role erasing the presence of CCs (eg. [1]). In this Section, we analyse our simulation paying special attention to the presence of CCs, and their relative abundances.

Following [1], we define a CC cluster as one with a $\geq 20\%$ reduction of its central temperature compared with the surrounding region. Using this definition, we have classified all the clusters in our sample into two groups: CCs and NCCs.

In Fig. 1, we plot the fraction of CCs as a function of gaseous mass at $z = 0$. We have binned the clusters using five linearly equispaced bins in the range $[10^{13}, 10^{15}]\,\mathrm{M}_{\odot}$. We compare our results (continuous line) with those by [9] (dotted line) and [2] (dashed line). As in [1], we obtain a fraction of $\sim 16\%$ of CC clusters and our results differ in the absolute numbers from the observational data, but more interestingly, we have confirmed the general trend of a decreasing number of CC clusters with cluster mass. Our most plausible explanation for the discrepancy between the absolute number of CC clusters in our simulation and the observational data by [2] has to do with the fact that no metal-dependent cooling has been considered in the simulation. This limitation could mimic some sort of uncontrolled non-gravitational feedback producing, therefore, some artificial reduction of the cooling, specially

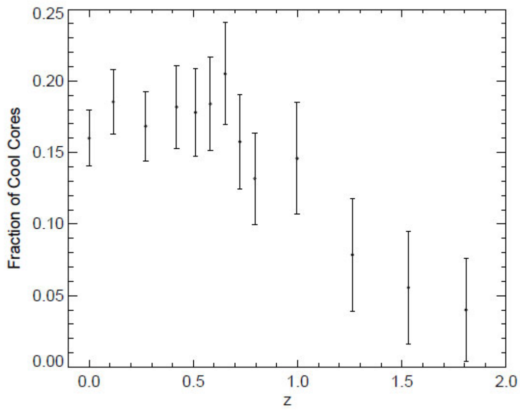

Figure 2: Fraction of CCs as function of redshift for the simulated clusters in our complete sample. Error bars show $\sqrt{N}$ uncertainties due to the number counts.

in systems where $kT < 2$ keV.

In Fig. 2, we plot the fraction of CCs in our sample as a function of the redshift from $z \sim 2$ until $z = 0$. Again, our results are fully consistent with the simulations by [1] and show no important change in the fraction of CCs backwards in time, at least back to $z \sim 1$. Our results are in contradiction with observational evidences showing an important variation in the fraction of CCs from $z = 0.5$ [15]. Before $z \sim 1$, we find a dramatic reduction in the fraction of CCs with time. As it would be expected, the abundance of CCs would be directly correlated with the hierarchical formation of the clusters. At the epoch of cluster formation, almost none of the clusters would have a CC. The formation of CCs would require the establishment of cooling flows which, eventually, and through a slow process will form the cool cores. However, once the clusters were fully formed, the major mergers would destroy the CCs, creating a population of NCC clusters. As the mergers are more dramatic in the more massive systems, this would explain the anticorrelation of the fraction of CCs and the mass of the clusters (see Fig. 1).

3.2 Scaling relations

The galaxy cluster sample studied in this contribution is biased towards the most massive clusters of our simulation. Therefore, the statistical properties of this sample must be taken with caution as the sample is far from being complete, due to the numerical limitations. In this subsection, we consider all clusters in our sample with temperature $T_{500} \geq 1$ keV.

In Fig. 3, several scaling relations are plotted: X-ray luminosity (left panel), mass (middle panel), and mean entropy (right panel) within the radius r_{500} against the temperature T_{500}. Our results can be fitted by the following scaling relations: $L \propto T^{2.5}$, $M \propto T^{1.5}$, and $S \propto T^{0.9}$. For completeness, we have compared our scaling relations with observational data (small dots in Fig. 3) by [3] and by [13]. Our results seem to be consistent with observational data, leaving aside all the uncertainties of such direct comparison.

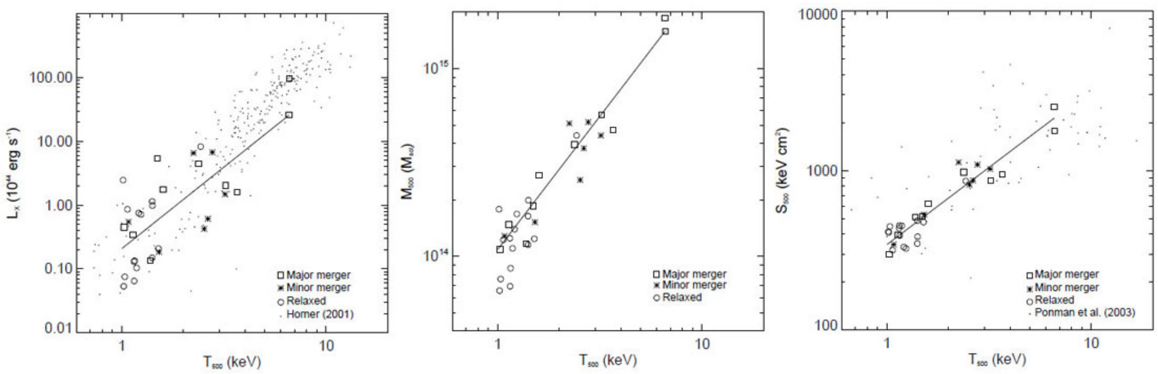

Figure 3: Scaling relations for our galaxy cluster sample. From left to right: integrated X-ray luminosity, mass, and mean entropy within the radius r_{500} against the temperature T_{500}. The different symbols represent the clusters in our sample, the continuous lines stand for the proper fittings, and the small filled dots represent observational data by [3] and [13], respectively.

Focusing on the effect of mergers, the results displayed in Fig. 3 show some degree of segregation, with most of the major and minor merger clusters located at well separated regions on the scaling relation plots. As a gross trend, the majority of clusters which have suffered mergers, are placed in zones with higher temperature and higher luminosity, mass, and entropy, respectively.

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 analyze the effects of galaxy cluster mergers as a source of feedback and reheating of the ICM. In order to do so, we have extracted and followed the evolution of the galaxy cluster like haloes in our simulation. These haloes have been studied directly from the simulation and without any resimulating scheme. We have studied their evolutionary histories and classified them into three categories (major merger, minor merger, and relaxed clusters) depending on the merger events they have undergone.

The fraction of clusters in our sample that has CCs has been computed at several redshifts. At $z = 0$, our results are fully compatible with previous AMR simulations by [1], although seem to differ with the results of the SPH simulation by [6]. We have compared the fraction of cool cores in our simulation with the observational data by [2] showing a similar trend, that is, the number of clusters with cool cores decreases with the cluster mass. Unfortunately, the absolute numbers of CCs in our simulation and the observations are quite different. Our explanation for this discrepancy would be related with the fact that no metal-dependent cooling has been considered in the simulation. In any case, it seems clear that there is an evident link between the merger events and the no existence of CCs. On the other hand, the time evolution of the fraction of CCs shows that this quantity has not changed substantially from $z \sim 0$ to $z \sim 1$. This result is compatible with previous simulations by [1] but in disagreement with observational data by [15].

Despite the resolution limitations, the scaling relations derived from our sample ($L \propto T^{2.5}$, $M \propto T^{1.5}$, and $S \propto T^{0.9}$) are consistent with previous results that do not introduce any extra reheating or feedback. We have found some degree of segregation in the scaling relations: systems that have experienced merger events are usually located at higher temperatures, luminosities, masses, and entropies, respectively, at the different scaling relation plots.

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. It is clear that feedback processes would also play a crucial role on the existence of CCs, but in the present simulation, where no relevant feedback mechanism – apart of the gravitational – has been taken into account, the effect of mergers is more outstanding.

Acknowledgments

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