The effect of radiative cooling on X-ray emission from clusters of galaxies

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Abstract. In this paper we use state-of-the-art N-body hydrodynamical simulations of a cosmological volume of side 100 Mpc to produce many galaxy clusters simultaneously in both the standard cold dark matter (SCDM) cosmology and a cosmology with a positive cosmological constant (ΛCDM). We have performed simulations of the same volume both with and without the effects of radiative cooling, but in all cases neglect the effects of star formation and feedback. With radiative cooling clusters are on average five times less luminous in X-rays than the same cluster simulated without cooling. The importance of the mass of the central galaxy in determining the X-ray luminosity is stressed.

1 Introduction

Clusters of galaxies are the largest virialised structures in the Universe, evolving rapidly at recent times because in hierarchical cosmologies big objects form last. Even at moderate redshifts the number of large dark matter halos in a cold dark matter Universe with a significant, positive cosmological constant is higher than in a standard cold dark matter Universe and it is precisely because both the number density and size of large dark matter halos evolve at different rates in popular cosmological models that observations of galaxy clusters provide an important discriminator between rival cosmologies.

The simulations we have carried out follow 2 million gas and 2 million dark matter particles in a box of side 100 Mpc. We have performed both a SCDM and a ΛCDM simulation with the parameters; \( \Omega = 1.0, \Lambda = 0.0, h=0.5, \sigma_8 = 0.6 \) for the former and \( \Omega = 0.3, \Lambda = 0.7, h=0.7, \sigma_8 = 0.9 \) for the latter. The baryon fraction was set from Big Bang nucleosynthesis constraints, \( \Omega_b h^2 = 0.015 \) and we have assumed an unevolving gas metallicity of 0.3 times the solar value. These parameters produce a gas mass per particle of \( 2 \times 10^9 \text{M}_\odot \).

These simulations produce a set of galaxies that fit the local K-band number counts\textsuperscript{[4]}. The brightest cluster galaxies contained within the largest halos are not excessively luminous for a volume of this size, unlike those found in previous work\textsuperscript{[5,7]} and presumably\textsuperscript{[11]} (although they do not state a central galaxy mass or galaxy luminosity). The fraction of the baryonic material that cools into galaxies within the virial radius of the large halos in our simulation is typically around 20 percent, close to the observed baryonic fraction in cold gas and stars. This is much less than the unphysically high value of 40 percent reported by\textsuperscript{[9]}. 

2 Results

For each of the 20 largest clusters from each simulation we follow \cite{8} in using the following estimator for the bolometric X-ray luminosity of a cluster,

$$L_X = 4 \times 10^{32} \sum \rho_i T_i^{\frac{1}{2}} \text{ergs}^{-1}$$

(1)

where the sum is over all the gas particles with temperatures above 12000 K within the specified radius. Temperatures are in Kelvin and densities are relative to the mean gas density in the box. We plot these bolometric luminosities as a function of radius for each of our relaxed clusters in figure 1. For the simulation without cooling the clusters are several times more luminous than those from the cooling run. This contradicts previous results \cite{5, 11, 7} who all found the X-ray luminosity increased if cooling was turned on. The cooling clusters are less luminous than their counterparts in the simulation without cooling because they have lower central temperatures and similar central densities. Most of the emission coming from the non-cooling clusters comes from the central regions, with little subsequent rise in the bolometric luminosity beyond 0.3 times the virial radius whereas for the majority of the cooling clusters the bolometric luminosity continues to rise out to the virial radius.

There has been much debate in the literature centering on the X-ray cluster $L_X$ versus $T$ correlation. The emission weighted mean temperature in keV is plotted against the bolometric luminosity within the virial radius for all our clusters in figure 2. The filled symbols represent the relaxed clusters and the open symbols denote those clusters that show significant substructure. Clearly the simulation without cooling produces brighter clusters at the same temperature. All 3 sets of objects display an $L_X - T$ relation although there are insufficient numbers to tie the trend down very
tightly. Also plotted in figure 2 are the observational data [1]. Our clusters are smaller and cooler because they are not very massive (due to our relatively small computational volume) but span a reasonable range of luminosities and temperatures.

3 Discussion

Implementing cooling clearly has a dramatic effect on the X-ray properties of galaxy clusters. Without cooling our clusters closely resemble those found by previous authors ([2] and references therein). These clusters appear to have remarkably similar radial densities and bolometric X-ray luminosity profiles, especially when those with significant substructure are removed.

With cooling implemented the cluster bolometric X-ray luminosity profiles span a broader range. The formation of a central galaxy within each halo acts to steepen the dark matter profile, supporting the conclusion of the lensing studies [6] that the underlying potential that forms the lens only has a small core. For the largest cluster, a significant amount of baryonic material has cooled and built up a large central galaxy. This localised mass deepens the potential well and contains hot gas with a steeply rising density ($\rho \propto r^{-2.75}$ in the inner regions). For this cluster around 80 percent of the bolometric X-ray emission comes from the galactic region and this must therefore be viewed as a lower limit as the central emission is unresolved. Such a large central spike to the X-ray emission is already only weakly consistent with the latest observational data [3]. For the remaining 19 clusters the central galaxy is not so dominant and a shallower central potential well is formed. In these cases the slope of the central hot gas is $\rho \propto r^{-0.5}$ and the total X-ray emission is well resolved. In principle, the presence of a large galaxy could resolve the problem of the slope of the X-ray luminosity - temperature relation. In large clusters, large central galaxies are more likely to be present and this galaxy deepens the local potential well, boosting the emission above the theoretically expected $L_X \propto T^2$ regression line. Getting a reasonable amount of material to cool into the central galaxy is seen to be of vital importance.

4 Conclusions

We have performed two N-body plus hydrodynamics simulations of structure formation within a volume of side 100 Mpc, including the effects of radiative cooling but neglecting star formation and feedback. By repeating one of the simulations without radiative cooling of the gas we can both compare to previous work and study the changes caused by the cooling in detail. A summary of our conclusions follows.

(a) The bolometric luminosity for the clusters with radiative cooling is around five times lower than for matching clusters without it. Except for the largest cluster where the massive central galaxy produces a deep potential well the X-ray luminosity profile is less centrally concentrated than in the non-cooling case with a greater contribution coming from larger radii. This effect assists in convergence as we are less dependent upon the very centre of the cluster profile.

(b) The spread of the X-ray luminosity – temperature relation is well reproduced by our clusters. Our non-cooling clusters lie close to the regression line suggested by [2] and
have a similar slope ($\rho \propto r^{-2}$). We suggest that the increasing dominance of a large central galaxy on the local potential may produce the luminosity excess that drives the observed X-ray luminosity – temperature relation away from the theoretically predicted slope.

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