The evolution of stellar and dark matter density in EAGLE brightest cluster galaxies

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Abstract. We use the EAGLE (Evolution and Assembly GaLaxies and their Environments) simulations, with the 50 co-moving Mpc a side box, with and without the effect of active galactic nuclei (AGN) to study dark matter distribution and stellar density in central galaxies. The simulations allow us to study cosmological structures at various redshifts which are chosen at 0, 0.27 and 0.87. We study the brightest cluster galaxy (BCG) in the largest galaxy cluster at these redshifts. The dark matter profile of the galaxy in the simulation with AGN exhibits a flat core, while its counterpart in the simulation without AGN is cuspy at all redshifts. The stellar density in the galaxy resembles the corresponding dark matter profile at all radii. At outer radii, the stellar density profile in the simulation with AGN changes dramatically from high to low redshift. We conclude that the energetic process of AGN in the simulation can effect both the stellar and dark matter components in central galaxies. As the box size is relatively small and the result is based on only central galaxies of small clusters, the study does not cover a wide dynamic range. The baryonic feedback effect on dark matter needs to be further explored on larger scales for cosmologists to correctly constrain cosmological parameters.

1. Introduction

Galaxy clusters are the largest gravitationally bound systems in the universe and are used as a cosmological probe. They are the result of hierarchical structure formation and are exploited as a tool to study matter distribution in the universe. However, the formation and evolution of large scale structure is non-linear and is driven by baryonic processes through cosmic time. Understanding the behavior and evolution of dark and baryonic matter is key to provide an accurate scenario of structure formation.

Not only are the baryonic effects needed to be fully understood as they are crucial in regulating the amount of galaxy and star formation, it has been shown to have cosmological implications such as in predicting matter power spectrum [1], galaxy clustering [2], and constraining dark energy [3]. One of the most energetic baryonic processes in a cluster is feedback from active galactic nuclei (AGN). Numerical simulations have shown that the feedback plays a vital role in determining spatial distribution of stars and dark matter in the central regions of clusters [4]. In particular, as AGN feedback can heat gas and expel it from the central region of the halo, it can also modify the dark matter profile, resulting in creating dark matter cores [5].

To explore the effect of baryonic processes in central region of a cluster, we use the ‘Evolution and Assembly of GaLaxies and their Environments’ (EAGLE) simulations to follow the evolution
of matter distribution in the largest galaxy formed in the largest structure at 3 redshifts. Such a galaxy is equivalent to the brightest cluster galaxy (BCG) which is the most luminous galaxy in a cluster, normally located at the center of the host.

2. The EAGLE simulations
The Virgo consortium’s Evolution and Assembly of GaLaxies and Environments (EAGLE) is a suite of cosmological, hydrodynamical simulations of a standard ΛCDM universe. The simulations allow us to study the formation and evolution of galaxies formed in cosmological volumes with a range of different baryonic effects. In this work, we follow the evolution of the largest galaxy formed in the largest cluster in two models, the ‘NoAGNL0050N0752’ and ‘AGNdT9L0050N0752’ models [6], hereafter NoAGN and AGNdT9, respectively. Both simulation boxes are 50 comoving Mpc (cMpc) on a side with $752^3$ particles each of gas and dark matter, of $1.81\times10^6 \, M_\odot$ and $9.70\times10^6 \, M_\odot$, respectively, with the maximum proper softening length of 0.7 kpc. The AGNdT9 simulation implements radiative cooling, energy feedback from star formation and AGN where feedbacks are calibrated to match the observed $z=0$ galaxy stellar mass function (GSMF), with AGN heating temperature of $\Delta T_{\text{AGN}} = 10^9 \, \text{K}$ and subgrid black hole accretion disc viscosity, while the NoAGN model is without black holes or AGN feedback. All simulations use cosmological parameters by the Planck Collaboration [7] with $h = 0.6777$, $\Omega_m = 0.307$, $\Omega_b = 0.04825$ and $\Omega_{\Lambda} = 0.693$.

3. The galaxy properties
We follow the evolution of matter properties of the largest central galaxies at 3 redshifts, $z = 0$, 0.27, and 0.87, representing the local, intermediate and high redshift, respectively, of the host galaxy cluster. Haloes are identified and presented with properties in the database\(^1\), at which the particle data can also be accessed. Table 1 lists the halo virial radius, defined as a radius at which the average total density is 200 times the critical density, that the galaxy resides in, the total, dark matter, stellar, gas mass (and black holes mass only in the AGNdT9 simulation) of the galaxy, at different redshifts. Without the effect of AGN, a lot of stars are formed in the central galaxies, as should be expected.

| $z$ | $r_{200}$ (ckpc) | $M_{\text{total}} \times 10^{14}$ ($M_\odot$) | $M_{\text{dm}} \times 10^{14}$ ($M_\odot$) | $M_{\star} \times 10^{12}$ ($M_\odot$) | $M_{\text{g}} \times 10^{13}$ ($M_\odot$) | $M_{\text{bh}} \times 10^9$ ($M_\odot$) |
|-----|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0.00 | 1144            | 1.41            | 1.20            | 0.75            | 2.01            | 6.69            |
| 0.27 | 1253            | 1.04            | 0.89            | 0.55            | 1.42            | 3.10            |
| 0.87 | 914             | 0.27            | 0.24            | 0.19            | 0.28            | 2.18            |

| $z$ | $r_{200}$ (ckpc) | $M_{\text{total}} \times 10^{14}$ ($M_\odot$) | $M_{\text{dm}} \times 10^{14}$ ($M_\odot$) | $M_{\star} \times 10^{12}$ ($M_\odot$) | $M_{\text{g}} \times 10^{13}$ ($M_\odot$) | $M_{\text{bh}} \times 10^9$ ($M_\odot$) |
|-----|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0.00 | 1152            | 1.46            | 1.24            | 1.91            | 2.02            | -               |
| 0.27 | 1262            | 1.04            | 0.88            | 1.49            | 1.49            | -               |
| 0.87 | 928             | 0.28            | 0.29            | 0.06            | 0.36            | -               |

\(^1\) http://icc.dur.ac.uk/Eagle/database.php
Figure 1. Dark matter (solid curve) and stellar density (dashed curve) profiles, with respect to the critical density, $\rho_c$, at $z = 0.00$ (top), 0.27 (middle), and 0.87 (bottom), in the NoAGN (left panels) and AGNdT9 (right panels) models. The best fitted NFW and Burkert profiles for dark matter are shown as dotted and dash-dotted line. The dashed and solid vertical lines represent the stellar half mass radius and dark matter half mass radius of the galaxy, respectively. Power law slopes of dark matter and stellar densities are shown.
4. Dark matter and stellar densities

We calculate the 3D spherically-averaged density profiles of dark matter and stars. In figure 1, the presence of AGN feedback results in expelling both the stars and dark matter to create the flat core, while the profiles in the NoAGN model are cuspy. To characterise the dark matter profile, we use the NFW profile [8] and Burkert profile [9] to fit the cuspy and cored dark matter profiles, respectively. The profiles can be written as

\[ \rho(r) = \frac{\rho_0}{(\delta + \frac{r}{r_s})^\gamma (1 + \frac{r}{r_s})^\alpha}, \]

where \( \rho_0 \) and \( r_s \) are density and scale radius parameters which vary from halo to halo, the parameters \( (\alpha, \beta, \gamma, \delta) \) are equal to \( (1, 3, 1, 0) \) and \( (2, 3, 1, 1) \) for the NFW and Burkert profile, respectively. In the NoAGN model, stars and dark matter are highly concentrated in the central region, while in the AGNdT9 model are more spread out. The best fit scale radius parameters are presented in Table 2. Outside the core, at the radius larger than the stellar half mass radius out to the dark matter half mass radius, there are 2 power law slopes that fit the profile. The inner slopes are generally steeper in the NoAGN model at intermediate and high redshifts than those in the AGNdT9 model, and change more dramatically from high to low redshift. On the other hand, the power law slope of the stellar density profiles in the AGNdT9 model change more dramatically at these radii.

| \( z \) | \( \alpha_{dm,1} \) | \( \alpha_{dm,2} \) | \( \alpha_{star} \) | \( r_{s,NFW} \) (ckpc) | \( r_{s,Burkert} \) (ckpc) |
|---|---|---|---|---|---|
| AGNdT9 |
| 0.00 | -1.520 | -2.147 | -2.776 | 279.986 | 119.991 |
| 0.27 | -1.611 | -1.992 | -3.448 | 245.018 | 59.995 |
| 0.87 | -1.831 | -1.914 | -3.951 | 139.993 | 49.997 |
| NoAGN |
| 0.00 | -1.457 | -2.005 | -3.053 | 209.993 | - |
| 0.27 | -1.672 | -1.856 | -3.476 | 174.994 | - |
| 0.87 | -2.155 | -1.697 | -3.441 | 69.996 | - |

5. Summary and conclusion

We study the dark matter and stellar density profiles in central galaxies formed in the largest haloes in the EAGLE simulations, without and with the effect of AGN, i.e. the NoAGN and AGNdT9 simulations, respectively, at redshifts 0, 0.27 and 0.87. The galaxy mass is in the order of \( 1 \times 10^{14} \, M_\odot \) at the current redshift. Stars and dark matter are highly concentrated in the center in the NoAGN model, while they are more spread out in the AGNdT9 model at all redshifts. We conclude that the presence of AGN in the model effectively produces the flat core profiles, both of gas and dark matter. The cored dark matter profile in the AGNdT9 model is well fitted by the Burkert profile, while the cuspy profile in the NoAGN model can be fitted by the NFW profile. Outside the core, between the stellar half mass radius and dark matter half mass radius, the slope of the stellar density profile changes dramatically in the AGNdT9 model. Not only does the baryonic feedback result in the radial distribution of stars, it is shown to
have a direct impact on the dark matter profile, transforming from cusp to core. This will have direct implications on using galaxies and clusters for cosmological work. As the simulation box is relatively small, and the results are drawn from central galaxies of small clusters, we need to use larger boxes to cover a wide range of dynamical scales to further explore the effect baryonic feedback on dark matter.

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