Galaxies and subhaloes in $\Lambda$CDM galaxy clusters

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ABSTRACT

We combine 10 high resolution resimulations of cluster–sized dark haloes with semi-analytic galaxy formation modelling in order to compare the number density and velocity dispersion profiles of cluster galaxies with those of dark matter substructures (subhaloes). While the radial distribution of galaxies follows closely that of the dark matter, the distribution of dark matter subhaloes is much less centrally concentrated. The velocity dispersion profiles of galaxies are also very similar to those of the dark matter, while those for subhaloes are biased high, particularly in the inner regions of clusters. We explain how these differences, already clearly visible in earlier work, are a consequence of the formation of galaxies at the centres of dark matter haloes. Galaxies and subhaloes represent different populations and are not directly comparable. Evolution produces a complex and strongly position–dependent relation between galaxies and the subhaloes in which they reside. This relation can be properly modelled only by appropriate physical representation of the galaxy formation process.

Key words: methods: N-body simulations – methods: numerical – dark matter – galaxies: clusters: general – galaxies: haloes – galaxies: formation – galaxies: evolution – galaxies: stellar content

1 INTRODUCTION

A variety of observational indicators have recently converged to establish the $\Lambda$CDM cosmogony as the de facto standard model for the formation of structure in our universe (e.g. Spergel et al 2003). For the general class of such hierarchical models, Navarro, Frenk & White (1996, 1997) showed that the radial density profiles of nonlinear structures such as galaxy or cluster dark haloes are well represented by a simple fitting formula of “universal shape”. As new galaxy surveys have amassed homogeneous data for large samples of clusters, the mean radial profiles of both number density and velocity dispersion have been found to conform quite closely to these NFW predictions for the dark matter (Carlberg et al. 1997; Biviano & Girardi 2003). Models which follow galaxy formation and cluster assembly explicitly do reproduce such parallel galaxy and dark matter profiles, even though the relation between the luminosity and dark matter mass of individual galaxies shows a lot of scatter and is predicted to depend strongly on clustercentric distance (Diaferio et al. 2001; Springel et al. 2001).

The high resolution achieved by numerical simulations in recent years has allowed detailed study of the properties of dark matter substructure (subhaloes) within dark haloes (Tormen 1997; Ghigna et al. 1998, 2000; Klypin et al. 1999a, 1999b; Stoehr et al. 2002, 2003; De Lucia et al. 2004a; Diemand et al. 2004; Gill et al. 2004a, 2004b; Gao et al. 2004). These studies agree quite well on the structure, abundance and radial distribution predicted for subhaloes, once differences in numerical resolution are accounted for. On the other hand, a variety of contradictory conclusions have been drawn from comparison with the observed properties of luminous objects in galaxy haloes and galaxy clusters (compare the discussions in Moore et al. 1999; Klypin et al. 1999a; Stoehr et al. 2002, 2003; D’Onghia & Lake 2003; Desai et al. 2003; Diemand, Moore & Stadel 2004; Kravtsov et al. 2004; Willman et al. 2004). We argue below that these disagreements can in most cases be traced to insufficiently careful modelling of the relation between the properties of subhaloes and those of the galaxies they contain.

In particular, a number of recent studies have noted that the radial distribution of subhaloes within dark haloes is very shallow compared both to that of the dark matter and to that of observed galaxies in real clusters (Ghigna et al. 2000; De Lucia et al. 2004a; Diemand et al. 2004; Gill et al. 2004a; Gao et al. 2004). Some of these authors concluded that this difference may indicate a fundamental problem for the $\Lambda$CDM model, failing to notice that the earlier simulations of Springel et al. (2001) had followed substructure with comparable numerical resolution and showed that modelling baryonic processes can produce a galaxy pro-
file in good agreement with observation. This suggests there are serious inadequacies in a simple model where the luminosity (or kinematics) of a galaxy is simply related to the mass (or potential well depth) of the corresponding subhalo in a dark-matter-only simulation. With the assumptions of Springel et al. (2001) the relation between these properties shows very large scatter and depends systematically on radius within a cluster halo. This is because the stellar mass of galaxy is determined primarily by its halo mass at the time the stellar component was assembled rather than by its halo mass at the present day.

Semi-analytic models of the kind used by Springel et al. (2001) are an ideal tool to explore the relation between dark matter subhaloes and the galaxies they host. In this paper we use the improved semi-analytic model developed by De Lucia, Kauffmann & White (2004b) which is able to reproduce the observed luminosity functions, metallicities and colour-magnitude relations of cluster galaxies, as well as the metal content of the intracluster medium. We apply this model to a set of ten high resolution dark-matter-only resimulations of cluster formation in a ΛCDM universe, eight of which are also analysed in companion papers on the systematic properties of subhalo populations in ΛCDM dark haloes (Gao et al. 2004) and on the assembly of the central cusps of ΛCDM clusters (Gao et al. 2003).

This Letter is structured as follows. In Sec. 2, we briefly describe the simulations and the semi-analytic model used for this study. In Sec. 3, we study the spatial distributions and the velocity dispersion profiles of galaxies and dark matter substructures and we explain the differences between them. A discussion and a summary of our results are presented in Sec. 4.

2 THE SIMULATIONS AND THE SEMI–ANALYTIC MODEL

We use a set of ten N–body resimulations of the formation of a massive galaxy cluster in a ΛCDM Universe. The clusters range in mass $M_{200}$ from $4.5 \times 10^{14} h^{-1}M_\odot$ to $8.5 \times 10^{14} h^{-1}M_\odot$, and were initially identified in a cosmological simulation of a region $0.479 h^{-1}$Gpc on a side (Yoshida, Sheth & Diaferio 2001) and run with numerical parameters suggested by Power et al. (2003). Many of them have been studied previously Gao et al. (2003, 2004) and Navarro et al. (2003). These resimulations were carried out using the publicly available parallel N–body code GADGET (Springel, Yoshida & White 2001) with a particle mass of $5.12 \times 10^9 h^{-1}M_\odot$ and a force softening of $\epsilon = 5 h^{-1}$kpc. The cosmological parameters assumed were: $\Omega_0 = 0.3, \Omega_\Lambda = 0.7, h = 0.7$ (we adopt the standard convention $H_0 = 100 h\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$) and normalisation $\sigma_8 = 0.9$. Dark matter subhaloes are identified using the algorithm SUBFIND (Springel et al. 2001). All subhaloes containing at least 10 particles are tracked. The numerical data for each subhalo is stored at 50 times logarithmically spaced between $1+z = 40$ and $1+z = 1$ and tree structures are built to follow the formation and merger history of each halo and its subhaloes.

We follow the baryonic evolution using the semi-analytic model by De Lucia et al. (2004b). As in Springel et al. (2001), the model explicitly follows the evolution of the dark matter halo within which a galaxy forms, even after this halo is accreted by a larger object and becomes one of its subhaloes. The model also follows the chemical and photometric evolution of cluster galaxies in a self-consistent way, together with the chemical enrichment of the intracluster medium. De Lucia et al. (2004b) have shown that their model agrees with a large body of observational results for galaxies in the local Universe, both in clusters and in the field. We refer to the original paper for a more detailed description. In this study, we use their ‘feedback’ model which they find to be the only one able to reproduce the observed decline in baryon fraction from rich clusters to galaxy groups.

3 NUMBER DENSITY AND VELOCITY DISPERSION PROFILES FOR GALAXIES AND SUBHALOES

A number of recent studies have focussed on the radial distribution of subhaloes within dark matter haloes (Ghisina et al. 2001; Stoehr et al. 2003; De Lucia et al. 2004a; Diemand et al. 2004; Gao et al. 2004; Gill et al. 2004). These papers all agree that the subhalo profile is shallower than that of the underlying dark matter, and indeed their subhalo profiles are all very similar. Our own results are shown in the top left panel of Fig. 1 in the form of average radial profiles for the dark matter and for different subhalo samples within our 10 cluster resimulations. Note that there are roughly 50 subhaloes per cluster with $M_{sub}/M_{halo} > 2 \times 10^{-4}$ or with $V_{sub}/V_{halo} > 0.09$. (The two velocities here are the maximum circular velocities of the subhalo and of the cluster respectively.) There are about 350 subhaloes per cluster with more than 30 particles, which is the limit to which Gao et al. (2004) considered the subhalo distributions to be insensitive to resolution effects. The hashed region shows the scatter of the dark matter density profiles in our simulation set. Note that all densities have been normalised to the mean density inside the virial radius. The weak concentration of the subhalo distribution relative to that of the dark matter is evident for all our samples, although, as noted by Gao et al. (2004), the profile depends on how the subhalo population is defined (limited in mass or in circular velocity). In this same panel we also plot mean profiles for our model galaxies to two different magnitude limits. In contrast to the subhalo profiles and in agreement with Diaferio et al. (2001) and Springel et al. (2001), these coincide very nicely with the mean dark matter density profile.

In the top right panel of Fig. 1 we plot the average projected dark matter distribution together with the surface density profile of model galaxies to two different magnitude limits. For comparison, we also plot the average observed surface density profile for cluster galaxies in the CNOC survey (Carlberg et al. 1997). The surface density profiles for the simulations are obtained by projecting along the $x$, $y$ and $z$ axes in turn, keeping only dark matter particles and galaxies within $\pm 2R_{200}$ of cluster centre in depth, and binning up the projected density profiles out to a projected distance of $2R_{200}$. The plotted curves are then an average over three projections of each of ten simulations. The mean galaxy surface density profiles of our simulations agree ex-
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Figure 1. Top left: mean radial profiles for the dark matter (solid line), for model galaxies to two different magnitude limits (filled symbols), and for different subhalo samples, based on the ten clusters used in this study. Top right: mean projected surface density profiles for the dark matter (solid line) and for model galaxies to two different magnitude limits (dashed and dotted lines). The filled symbols represent the mean observed surface density profile of cluster galaxies in the CNOC survey (Carlberg et al. 1997). In these two panels, the hashed region represents the full scatter in dark matter profiles. Bottom panels: 3-D velocity dispersion profile (left) and line–of–sight velocity dispersion profile (right) for dark matter (solid line), for subhaloes containing at least 30 particles (dashed line), and for model galaxies to two different limiting magnitudes. The hashed regions and the error bars represent the standard 1σ scatter in the dark matter and the galaxy ($B < -17$) velocity dispersion profiles, respectively.

Fig. 1 clearly shows that subhaloes and galaxies have very different number density and velocity dispersion profiles in our simulations, despite the fact that we assume that extremely well both with the observational data and with the mean dark matter profile.

In the bottom panels of Fig. 1 we show the 3-D (left panel) and the line–of–sight (right panel) velocity dispersion profiles of dark matter particles, of galaxies and of subhaloes containing at least 30 particles. The hashed region and error bars represent the standard 1σ scatter of the dark matter and galaxy ($B < -17$) profiles among our ten resimulations. In agreement with previous studies (Ghigna et al. 1998; Colin et al. 2000; Diemand et al. 2004; Gill et al. 2004b), we find that the velocity dispersion of the subhalo population substantially exceeds that of the dark matter, particularly in the inner regions. On the other hand, there is at most a weak upward bias in the velocity dispersions of the model galaxies.

Fig. 1 clearly shows that subhaloes and galaxies have very different number density and velocity dispersion profiles in our simulations, despite the fact that we assume that
a galaxy forms at the centre of each dark halo and is carried along with it when it falls into a larger system and so becomes a subhalo. What is the origin of these differences? If one wants to relate the properties of subhaloes to those of the galaxies residing within them, the evolution of the baryonic component has to be tracked appropriately. This necessarily involves consideration of the full collapse, assembly, merging and tidal stripping history of each subhalo, rather than just its properties at the final time. Such tracking can be carried out conveniently and moderately realistically using semi–analytic techniques, as is done in this work.

Note that many of the model galaxies used to construct Fig. 1 are not associated with any resolved dark matter subhalo. In pure dark matter simulations, subhaloes can disappear once their mass falls below the resolution limit of the simulation. It may be that their dark matter content should indeed be reduced to such small values by tidal stripping, or it may be that proper inclusion of the effects of the baryonic component would make them more resistant to stripping and disruption, as originally envisaged by White & Rees (1978). Our semi–analytic model assumes that the visible galaxy survives even if the mass of the corresponding subhalo drops below the limit of our $N$–body simulation. We associate the galaxy with the most bound particle of its subhalo at the last time this could be identified, and we use this particle at later times to track the galaxy’s position and velocity. Such ‘orphan’ galaxies behave as individual $N$–body particles although we assume them to merge with the central galaxy of the cluster on a dynamical friction time–scale. At the resolution of our simulations, there are a substantial number of these ‘orphan’ galaxies and they are responsible for the large differences between the ‘galaxy’ and ‘subhalo’ profiles in the inner regions of our clusters. We demonstrate this by plotting the number density profile for all galaxies brighter than $B = -17$ which are still associated with subhaloes (i.e. not ‘orphan’ galaxies) as thin solid line in the top left panel of Fig. 1. Clearly these galaxies are substantially less concentrated than the galaxy population as a whole.

As discussed in Gao et al. (2004), the infall time and the retained mass of a subhalo are both strongly increasing functions of clustercentric radius. This implies that subhaloes in the inner regions of cluster haloes today were generally more massive in the past than similar mass but more recently accreted subhaloes in the outer regions. As first shown by Springel et al. (2001), this produces an increasing mass–to–light ratio as a function of the clustercentric distance. We show this for our present models in Fig. 2 where we plot mass–to–light ratio ($M/L_B$) and (circular velocity)$^4$–to–light ratio ($V^4/L_B$) for our model galaxies as a function of distance from cluster centre. Galaxies brighter than $M_B = -17$ from all ten resimulations are shown here. The velocity used in the right panel is defined as the maximum circular velocity of the associated subhalo. Outside the virial radius, these ratios are almost flat, reflecting the proportionality between the halo mass (or circular velocity to the fourth power) and the galaxy luminosity for isolated haloes (the Tully–Fisher relation).

About 55 per cent of the cluster galaxies brighter than $M_B = -17$ are not associated to any resolved subhalo, and so are assigned zero mass and circular velocity. In order to show the density distribution of these ‘orphan’ galaxies in Fig. 2, we assign them a mass–to–light ratio varying randomly between $-25$ and 0 and a (velocity)$^4$–to–light ratio between $-0.025$ and 0. Springel et al. (2001) show that this $M/L_B$ trend is present at a similar level in a simulation with almost ten times better resolution than those we use here. In addition, numerical convergence studies by Diemand et al. (2004) and by Gao et al. (2004) indicate that resolution effects on subhalo mass are relatively small for subhaloes with more than 30 particles and so cannot be responsible for the trends in Figure 2.

The radial variation of the mass–to–light ratio of cluster galaxies reflects the fact that tidal stripping is very efficient in reducing the masses of subhaloes within larger systems but is assumed to have much less effect on the luminosity and structure of the galaxies which reside at their centres. In such a situation, selecting subhaloes above a certain mass (or circular velocity) results in a population with very different properties from a galaxy population selected above a certain limiting magnitude.

4 SUMMARY AND DISCUSSION

In this Letter, we have implemented a semi–analytic treatment of galaxy formation on ten high resolution resimulations of galaxy cluster evolution in order to study the number density and velocity dispersion profiles predicted for galaxies and for dark matter subhaloes in ΛCDM galaxy clusters. In agreement with previous work, we find galaxy profiles that agree well both with simulated dark matter profiles and with observed galaxy profiles, but subhalo profiles with much weaker central concentration and with substantially higher velocity dispersion.

We show that these differences are due to a strong increase in the mass–to–light (or circular velocity)$^4$–to–light ratio of galaxies as a function of the distance from cluster centre. This trend is caused by tidal stripping which rapidly reduces the mass of dark matter subhaloes once they are accreted onto a larger structure, while only weakly affecting the galaxies at their centres. In related work, De Lucia et al. (2004a) and Gao et al. (2004) examine in considerably more detail the efficiency of tidal stripping, showing that the longer a substructure spends in a massive halo, the larger is the destructive effect. As they demonstrate explicitly, subhaloes are constantly being erased and being replaced by newly infalling haloes. Our semi–analytic model assumes that this process does not, however, destroy the galaxy at the centre of each subhalo, which has typically accumulated a substantial and strongly bound stellar component during earlier evolutionary stages.

Much of the work on substructure within dark matter haloes has attempted to link simulated substructure to observed galaxies by assuming a constant mass–to–light ratio for subhaloes or by relating their maximum circular velocity to galaxy luminosity through the observed Tully–Fisher and Fundamental Plane relations. Our results show clearly, as did the earlier results of Springel et al. (2001), that such assumptions are very unlikely to give realistic results. Galaxies and subhaloes are not simply related. The luminosity of a galaxy cannot be inferred from the $z = 0$ properties of the subhalo which corresponds to it in a dark–matter–only $N$–body simulation. Indeed, many cluster galaxies have no corresponding subhalo in such a simulation, even though the
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Figure 2. Mass–to–light ratio (left) and (circular velocity)²–to–light ratio (right) for model galaxies brighter than B = −17 as a function of distance from cluster centre. Filled cycles connected by thick lines show median values as a function of radius; Dashed lines show the 80th percentile of the distribution. Galaxies that are not associated with any dark matter subhalo are assigned zero mass and circular velocity, but are displayed with a randomly generated small negative value of the ordinate so that they are visible in the plots.

haloes in which they originally formed were easily resolved by the simulation. The galaxy formation process must be treated appropriately to get results which are even qualitatively correct.

We note that these issues will not be addressed by carrying out dark matter simulations of higher resolution. The tests of Diemand et al. (2004) and Gao et al. (2004) show that subhaloes can be followed and their masses tracked at least roughly down to a limit of 20 particles or so, corresponding to subhalo masses around $10^{10} M_\odot$ for the simulations in this paper. This is below the observed stellar mass of the galaxies in the real samples with which we are comparing our models. Thus dynamical evolution becomes dominated by the visible components of galaxies before our simulations run into resolution problems. Any improvement over our current simple semi-analytic assumptions will require explicit modelling of structure in the stellar component of cluster galaxies.

Finally we note that although this paper has dealt with cluster–sized haloes only, the same caveats apply also to galaxy– and group–sized haloes. Only through a full treatment of the baryonic physics, is it possible to carry out a detailed comparison between theoretical results and observational data. A complex network of actions and back–reactions regulates the evolution of the galaxy components we see, and any comparison of simulated subhaloes to observed galaxies must consider the time–integrated effect of these processes or risk serious error.

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REFERENCES

Biviano A., Girardi M., 2003, ApJ, 585, 205
Carlberg R. G., Yee H. K. C., Ellingson E., 1997, ApJ, 478, 462
Colin P., Klypin A. A., Kravtsov A. V., 2000, ApJ, 539, 561
Desai V., Dalcanton J. J., Mayer L., Reed D., Quinn T., Governato F., 2004, preprint, astro-ph/0311511
D’Onghia, E. & Lake, G., 2003, ApJL submitted, preprint, astro-ph/0309735
De Lucia G., Kauffmann G., Springel V., White S. D. M, Lanzoni, B., Stoehr, F., Tormen, G., Yoshida, N., 2004a, MNRAS, 348, 333
De Lucia G., Kauffmann G., White S. D. M, 2004b, MNRAS, 349, 1101
Diaferio A., Kauffmann G., Michael B., White S. D. M., Schade D., Ellingson E., 2001, MNRAS, 323, 999
Diemand, J., Moore, B., Stadel, J., 2004, MNRAS submitted, preprint, astro-ph/0403160
Gao, L., Loeb, A., Peebles, P. J. E., White, S. D. M., Jenkins, A., 2003, ApJ submitted, preprint, astro-ph/0312499
Gao, L., White, S. D. M., Jenkins, A., Stoehr, F., Springel, V., 2004, MNRAS submitted, preprint, astro-ph/0404589
Ghigna S., Moore B., Governato F., Lake G., Quinn T., Stadel J., 1998, MNRAS, 300, 146
Ghigna S., Moore B., Governato F., Lake G., Quinn T., Stadel J., 2000, MNRAS, 544, 616
Gill S. P. D., Knebe A., Gibson B. K, Dopita M. A., 2004a, MNRAS in press, preprint, astro-ph/0402455
Gill S. P. D., Colberg J. M., Diaferio A., White S. D. M., 1999, MNRAS, 303, 188
Klypin A., Gottloeber S., Kravtsov A. V., Khokhlov A., M., 1999a, ApJ, 1999, 516, 530
Klypin A., Kravtsov, A. V., Valenzuela, O., Prada F., 1999b, ApJ, 522, 82
Kravtsov A. V., Gnedin O. Y., Klypin A. A., 2004, ApJ submitted, preprint, astro-ph/0401088
Moore B., Ghigna S., Governato F., Lake G., Quinn T., Stadel J., Tozzi P., 1999 ApJ, 524, 19
Navarro J. F., Frenk C. S., White S. D. M., 1997, ApJ, 490, 493
Navarro J. F., Hayashi E., Power C., Jenkins A., Frenk C. S., White S. D. M., Springel V., Stadel J., Quinn T. R., 2004, MNRAS, 349, 1039
Power C., Navarro J. F., Jenkins A., Frenk C. S., White S. D. M., Springel V., Stadel J., Quinn T., 2003, MNRAS, 338, 14
Spergel D.N. et al., 2003, ApJS, 148, 175
Springel V., Yoshida N., White S. D. M., 2001a, New Ast. 6. 79
Springel V., White S. D. M., Tormen G., Kauffmann G., 2001b, MNRAS, 328, 726
Stoehr F., White S. D. M., Tormen G., Springel V., 2002, MNRAS, 335, L84
Stoehr F., White S. D. M., Springel V., Tormen G., Yoshida N., 2003, MNRAS, 345, 1313
Tormen G., 1997, MNRAS, 290, 411
Willman B., Governato G., Dalcanton J. J., Reed D., Quinn T., MNRAS submitted, 2004, preprint, astro-ph/0403001
White S. D. M., Rees M. J., 1978, MNRAS, 183, 341
Yoshida N., Sheth R. K., Diaferio A., 2001, MNRAS, 328, 669