THE DESCENDENTS OF LYMAN BREAK GALAXIES IN GALAXY CLUSTERS:
SPATIAL DISTRIBUTION AND ORBITAL PROPERTIES

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ABSTRACT

We combine semi–analytical methods with a ultra-high resolution simulation of a cluster (of mass \(2.3 \times 10^{14} h^{-1} M_\odot\) and \(4 \times 10^6\) particles within its virial radius) formed in a standard CDM universe to study the spatial distribution and orbital properties of the present–day descendents of Lyman Break galaxies (LBG). At redshift 3 we find a total of 12 halos containing at least one Lyman Break galaxy in the region that will later collapse to form the cluster itself. At the present time only five of these halos survive as separate entities inside the virial radius, having been stripped of most of their dark matter. Their circular velocities are in the range 200 – 550 km/sec. Seven halos merged together to form the central object at the very center of the cluster. Using semi-analytical modeling of galaxy evolution we show that descendents of halos containing Lyman Break galaxies now host giant elliptical galaxies such as those typically found in rich galaxy clusters. All galaxy orbits are very radial, with a pericenter to apocenter ratio of about 1:5. The orbital eccentricities of LBG descendents are statistically indistinguishable from those of the average galaxy population inside the cluster, suggesting that the orbits of these galaxies are not significantly affected by dynamical friction decay after the formation of the cluster’s main body. In this cluster, possibly due to its early formation time, the descendents of Lyman break galaxies are contained within the central 60% of the cluster virial radius and have an orbital velocity dispersion lower than the global galaxy population, originating a mild luminosity segregation for the brightest cluster members. Mass estimates based only on LBG descendents (especially including the central cD) reflect this bias in space and velocity and underestimate the total mass of this well virialized cluster by up to a factor of two compared to estimates using at least 20 cluster members.

Subject headings: dark matter — cosmology: observations, theory — galaxies: clusters, formation

1. INTRODUCTION

The implementation of a simple color selection technique to select efficiently galaxies at redshift larger than 2.5 (Steidel et al. 1996, Madau et al. 1996, Steidel et al. 1999, Fontana et al. 1999) revealed a population of blue, actively star forming galaxies at high redshift. Galaxies as bright as those observed are likely hosted inside the most massive halos at high z (Bagla 1998, Baugh et al. 1998, Katz, Hernquist & Weinberg 1999, Coles et al. 1998, but see Somerville, Primack & Faber 1998 and Kolatt et al. 1999 for a slightly different view). These halos are more clustered (a bias factor of the order of 2-5) compared to the general distribution, providing strong support (Adelberger et al. 1998, Giavalisco et al. 1998) to models of biased galaxy formation (Davis et al. 1985). Under the effect of gravitational instability these large halos will merge together and form the massive clusters we see today (Governato et al. 1998). Semi–analytical models (Baugh et al. 1998) further suggested that the present day descendents of LBG in protoclusters would be preferentially giant ellipticals with an old red population of stars.

Bright, red cluster members reside preferentially at the center of clusters and often have been found to have a lower orbital velocity dispersion (Chincarini & Rood 1977, Mellier et al. 1988, Biviano et al. 1992, Whitmore et al. 1993, Biviano et al. 1996, Carlberg et al. 1997) than the global cluster population. Recent results with full redshift information for a large sample of clusters (Adami, Biviano & Mazure 1998, Ramirez, de Souza & Schade 2000) and photometric observations of the Coma cluster (Kashikawa 1998) give support to these claims. Adami et al. 1998 based on a simple theoretical modeling, suggest that orbits of the brightest galaxies have to be circular to explain the decrease in velocity dispersion and at the same time be consistent with the hypothesis of dynamical equilibrium at the cluster center.

Indeed theoretical prejudice would expect to find galaxies formed in massive halos at high redshift to reside preferentially in the central region of clusters. Moore et al. (1998) and White & Springel (1999) showed that, in CDM cosmologies, matter already in virialized objects at high redshift makes a large fraction of the mass within the central regions of present day clusters. Dynamical friction, if acting efficiently on a long enough time scale could further segregate massive halos at the center of clusters (but the effect is likely to be small; see Ghigna et al. 1998 and Colpi, Mayer & Governato 1999, hereafter CMG99). In recent years, numerical and analytical studies of galaxy clusters have rapidly increased in resolution and detail (e.g. Katz & White 1993, Carlberg 1994, Frenk et al. 1996, Fusco–Femiano & Menci 1998, Tormen, Diaferio & Syer 1998, 1999, Biviano et al. 1996, Carlberg et al. 1997) than the global cluster population.

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Fig. 1.— Circular velocity $V_c$ (see text) vs. distance from the cluster center at $z = 0.1$. Large filled dots are descendents of LBGs, small filled dots are the 20 brightest cluster members. Small empty circles show the whole cluster population with $V_c > 70$ Km/sec. Inner panel: $V_c$ vs. orbital pericenter. Symbols are as in the main panel.

Klypin et al. 1999). Frenk et al. (1996) found mild spatial segregation of the most massive galaxies, they also included gas dynamics and a simple description of star formation processes.

In this work we use a unified approach that couples a state of the art numerical simulation of a galaxy cluster with a detailed, semi-analytical description of galaxy formation inside individual dark matter halos. This method will allow us to study the spatial and orbital distribution of galaxies in a moderately rich cluster with unprecedented detail and to investigate the relation between LBGs at high redshift and present day cluster galaxies.

2. COUPLING N-BODY SIMULATIONS AND SEMI-ANALYTICAL MODELS

2.1. The Cluster simulation

We used a very high resolution N-body (i.e. collisionless) simulation of a galaxy cluster (slightly more massive than Virgo, $2.3 \times 10^{14} h^{-1} M_{\odot}$) within the virial radius, defined as the radius where $\rho(r < R) \sim 200\rho_{\text{crit}}$ formed in a cluster normalized SCDM cosmology. This cluster contains over $4 \times 10^6$ particles within the virial radius (it is described in full detail in Ghigna et al. 1998, G98, Ghigna et al. 1999, G99, and Lewis et al. 1999). The effective spatial resolution is of the order of $1.0 h^{-1} \text{kpc}$, and we are able to resolve substructure halos with circular velocities $V_c$ down to 50 km/sec and with pericenters larger than $50 h^{-1} \text{kpc}$, a significant improvement compared with all previous works (here $V_c$ is defined as $\sqrt{GM(<r)/r}$).

The cluster forms through major mergers at redshift about 0.5 (defined as when its main progenitor has roughly 50% of the final cluster mass), accreting additional mass and galaxies at later times. It is well virialized and close to dynamical equilibrium by the present time (see G98 fig.1).

In this high resolution simulation, numerical overmerging (e.g., Moore, Katz & Lake 1996) is likely to be almost negligible, especially for the most massive halos. We can follow the evolution of thousands of halos as they participate in the build up of the cluster and subsequently orbit inside it. Even if severely stripped by the cluster tidal field, virtually all halos maintain their identity once inside the cluster, and only a few get destroyed by the tidal field or decay by dynamical friction at its center (see G99 for a full discussion).

Therefore, within this simulation is possible to follow the descendents of all halos and specifically those associated with LBG (see next subsection) through subsequent outputs to the present time. We first located dark matter halos inside the clusters with the algorithm SKID (see G98 and G99 for details, Springel 1999 for an alternative method) at the final time of the simulation and traced them back to dark matter halos at $z = 3$. High $z$ halos were identified with “Friends-of-Friends” (FOF, Davis et al. 1985), using a linking length = 0.2 the initial grid spacing, as FOF gives more robust masses for halos outside larger virialized structures. At $z = 3$ the region containing the cluster has yet to collapse, but hundreds of smaller halos have already formed within a complex network of filaments. For each halo we measured mass and circular velocity at their virial radius at high $z$ and at their individual tidal radii as imposed by the cluster potential at the present time (again see G98 for details).

2.2. Semi-analytical galaxy formation

The growth of dark matter halos can be followed both with N-body simulations and the extended Press & Schechter approach (or PS, see Press & Schechter 1974, Bower 1991, Bond et al. 1991). Within the semi-analytical approach a simple set of equations then describes the cooling of gas inside the dark matter halos and the subsequent star formation history, predicting size, lu-
minosities (including the effects of dust), colors and the morphology of galaxies formed inside these halos (Kauffmann, White & Guiderdoni 1993, Cole et al. 1994, Cole et al. 2000). We used the approach first outlined in Cole et al. 1994 and then further developed in Baugh et al. 1998 and Cole et al. 2000. This approach is remarkably successful in predicting the main properties of high redshift and local galaxies with a minimum set of constrained parameters (Baugh et al. 1998, see also Somerville & Primack 2000). However, the semi-analytical method based on the PS alone cannot recover the full 3D distribution of galaxies, making the full N-body simulations necessary.

For each halo identified at redshift 3 in the N-body simulation and for the whole cluster at the present time we used the semi-analytical approach (and so a PS merging history) to determine their galaxy content. At the present time the halos present inside the cluster are paired with semi-analytical cluster galaxies based on their circular velocity. Statistically this is equivalent to using merger trees obtained directly from N-body simulations (see Governato et al. 1998, Benson et al. 1999). As a test we looked at a set of different merger tree histories for a few clusters of the same mass as the one in our simulation to verify that the scatter introduced by our approach on the average properties as a function of circular velocities of the galaxy population was negligible. In fact, the galaxies produced with the semi-analytical approach show a rather tight luminosity-circular velocity relation, independently of the details of their merging history or of that of the parent cluster. This simple approach is then quite adequate for our purpose of broadly defining the types of galaxies hosted both in massive halos at high $z$ and inside their cluster descendants at the present time as a function of their mass (see Kauffmann et al. 1999, Springel 1999 for an approach based on the full merger trees obtained from N-body simulations).

Our procedure gives the properties of the galaxies hosted inside each given halo complete with full dynamical information (position and velocity inside the cluster). Once galaxies were placed inside dark matter halos, we selected at redshift of 3 those that, applying the same criteria, would have been selected as LBGs (Steidel et al. 1996). At the final time we then compare the properties of their descendants vs. those of the 20 brightest cluster members (comparable to the number of redshift usually measured for a single real cluster) and the whole cluster galaxy population.

3. RESULTS: THE DESCENDENTS OF LYMAN BREAK GALAXIES

At a redshift of 3 there are 12 halos with mass above $10^{12} M_\odot$ (the biggest object in the region that will later form the cluster has a mass of $3.2 \times 10^{12} h^{-1} M_\odot$). The semi-analytical approach predicts that each of these halos hosts at least one LBG galaxy, sometimes two. Indeed the N-body simulation already shows significant substructure inside them. There is some intrinsic scatter from one semi-analytical realization to another, depending on the details of the merging histories of individual halos. Sometimes smaller halos (on average less than one per realization) host LBGs, perhaps “observed” while they were at their maximum luminosity. This does not change our results significantly.

Halos containing LBGs are aligned along filaments and are rapidly flowing along them to form massive groups at $z \sim 1.5-0.75$ and then merge to form the main progenitor of the cluster by $z=0.5$. A large fraction (7 out of 12) merge together to form the central core of the cluster; 90% of the mass contained in their central part (defined as particles within the central $10 h^{-1}$kpc and likely traces of their stellar component ends up in the inner $125 h^{-1}$kpc of the cluster. Their barionic cores (not present in our simulation that includes only the dark, collisionless component) would then most likely merge together to form the central cD, as the decay time for any remnant of significant mass with orbital apocenters less than $100 h^{-1}$kpc from the cluster center is much shorter than the Hubble time. The five surviving halos have been tidally stripped and orbit in the central part of the cluster. According to the semi-analytical approach the descendents of LBGs are the most luminous ellipticals in the cluster at the present day. This result is independent of the details of the semi-analytical model used. In the approach used e.g. in Kolatt et al. (1999) a large number of Lyman Break Galaxies are small starbursting galaxies. These strong episodes of star formation originate from fly-bys between satellites inside more massive halos. In principle, these satellites could be stripped away from their parent halos and show a different spatial bias, making our conclusions dependent on the analytical modelling.

However, our simulation shows that none of the satellites of the massive halos at $z = 3$ survive as distinct entities by the present time, having merged with their hosts before the formation of the main body of the cluster.

3.1. Orbits and luminosity segregation

At $z = 0.1$ all LBG descendents can be found within the inner $0.6 h^{-1}$Mpc, i.e 60% of the virial radius of the cluster. They are more concentrated than the average cluster population (see Fig. 1). This is more evident in the distribution of the pericentric distances (inset of Fig. 1) and is true for apocenters as well. To strengthen the significance of the signal, we have verified that this holds true at a nearby epoch ($z = 0$). Using Wilcoxon test, we estimate that the probability of this spatial segregation happening by chance is less than 2%. Also considering that seven LBGs contributed to form the central galaxy, the mass contributed to the cluster by LBG descendents is more centrally concentrated compared with the global cluster population. As halos with large circular velocities are associated with galaxies of higher luminosities than the average galaxy cluster population, this causes a mild luminosity segregation. It is likely that the early formation time of this cluster and its following quiet merging history (it forms slightly earlier than average for its mass in a CDM cosmology; G98) contributed to this, as recent infall was not substantial enough to accrete massive halos at the outskirts of the cluster.

We then measured the orbital parameters for all galaxies inside our cluster (see Fig. 2). The orbital circularity $e$ is defined as the ratio of $J$, the orbital angular momentum, to $J_c$, the angular momentum of a circular orbit with the same energy. (Lacey & Cole 1994, Tormen 1997, G98). Here the orbital energy is defined assuming spherical symmetry for the cluster mass distribution and
the most bound particles for its center. There is no obvious difference in the distribution of circularities between descendents of LBG, the twenty brightest objects in the cluster and the rest of the galaxy population. The formal average values of $\epsilon$ for the three cases are 0.42, 0.59 and 0.54, respectively, with quite similar dispersions around the mean value ($\sim 0.3$). The dark matter background has similar orbital properties (G98). Results at $z = 0.1$ and 0 are similar.

This finding confirms results obtained with analytical and numerical models (van den Bosch et al. 1998, CMG99) that dynamical friction is not efficient at circularizing orbits of even the most massive and old galaxies inside clusters. We used the theory of linear response as described in CMG (which agrees extremely well with N-body experiments) to measure the orbital decay predicted for a group sized halo entering the cluster environment at $z = 1$ (i.e. the formation time of the main progenitor of the cluster itself). Once the effect of tidal stripping are included (see again CMG99) decay times are of the order of several times the Hubble time, and both pericenters and apocenters have changed only by a few percent by the present time. The luminosity segregation putatively observed in real galaxy clusters would then be an imprint of their hierarchical build up rather than the effect of subsequent strong dynamical evolution. This orbital segregation should be present (Springel, 2000 in preparation) or could even be larger in clusters formed in a open or flat cosmology, where clusters would form typically at higher redshift and where the accretion at late times slows down considerably.

Our simulation allows us for the first time to test the dynamical mass estimate based on a complete sample of substructure halos. We estimated the virial mass of the cluster from the galaxies’ projected velocity dispersions, using the classic estimator (Heisler, Bachall & Tremaine, 1985):

$$M_{VT} = (3\pi N/2G)\sum_{i<j} \frac{v_{p,i}^2}{R_{ij}}$$

where $v_{p,i}$ is the line of sight velocity and $R_{ij}$ the projected separation of a given galaxy pair. This estimator is useful for its simplicity, even if it overestimates the mass inside the virial radius by about 40% (see also Girardi et al. 1998 and references therein). We do not include galaxies in halos outside the virial radius, so that our sample is free of nearby back/foreground interlopers. Our results confirm previous results (Frenk et al. 1996, Tormen 1997) that the use of only the few brightest galaxies as mass estimators results in an underestimate of the cluster mass compared to using the whole galaxy sample, by up to a factor of 2 if the brightest galaxy is included (it has a very small velocity compared to the cluster galaxies as a whole). Additional scatter ($\sim 30\%$) is added when considering individual axial projections. Contrary to previous suggestions, this bias is not due to the most massive galaxies being on more circular orbits, but the fact that these galaxies sample only the central part of the cluster mass distribution and therefore have a lower velocity dispersions, as the peak in $V_c$ for the cluster as a whole is reached only at about $0.5 h^{-1}$Mpc, i.e. close to the apocenters of their orbits. Even excluding contamination from background and foreground objects at least 20 galaxies are needed to correctly sample the cluster potential and obtain a reliable mass measurement. Likely, even more redshifts would be needed in case the cluster had significant nearby structures (filaments or rich groups) in the near fore/background.

4. DISCUSSION

Using the high resolution simulation of a galaxy cluster coupled with semi-analytical methods of galaxy formation we identify at redshift of 3 a dozen halos hosting at least
one Lyman Break Galaxy. At the present time descendents of LBGs can be identified with the central cD galaxy and galaxies hosted in substructure halos with \( v_c \) in the range 200 to 550 km/sec. All 12 LBG descendents end up within the the inner \( \sim 0.5 \ h^{-1} \text{Mpc} \) (or 60% of the cluster virial radius); 7 merged together to form the central galaxy. These descendents are the most bright elliptical galaxies in the cluster. These results are largely independent from the details of the semi-analytical method used.

We confirm previous findings obtained with simulations of lower resolution (e.g. Frenk et al. 1996) that the most massive galaxies are likely to be centrally segregated and have lower orbital velocity dispersions when compared to the global cluster galaxy population. However, this effect is small, and harder to detect when only limited information (redshifts and positions projected on the sky plane) is available.

Spatial and velocity segregation for bright cluster members has long been observed in Coma (Mellier et al. 1988) and in larger samples of nearby clusters (Biviano et al. 1992, 1996), but the observational picture has been somewhat complicated by the small number of redshift available per cluster and by the fact that they have usually been collected only within the central part of the clusters themselves. Clearly a larger sample of observed and simulated clusters is needed to allow a more quantitative comparison between observations and theoretical predictions. We expect the segregation of bright ellipticals to be larger in well virialized clusters and in cosmologies were recent infall is small (e.g. open or flat CDM cosmologies).

Galaxies in our simulated cluster move on quite eccentric orbits, due to the almost radial infall typical of hierarchical clustering. There is no significant difference in the orbital eccentricity of different galaxy populations and the dark matter background. Also, orbits do not change in shape significantly over time (dynamical friction does not change the orbital eccentricity as shown also in CMG99).

Our analysis shows that to measure the virial mass of the cluster is crucial that a significant number of galaxies is used in order to correctly sample the cluster density profile. A sample, restricted to the most bright cluster members is likely to be biased and underestimate both the cluster total mass and velocity dispersion. In this simulated cluster, about twenty member galaxies sampling the mass distribution out to the virial radius are required for a correct estimate of the cluster total mass. This number could well be higher for a cluster far from virial equilibrium or with significant structures nearby. As our analysis shows, virial mass estimates suffer from an additional scatter of about 30%, due to velocity anisotropies along the cluster projection. This source of scatter cannot easily be removed increasing the number of galaxies.

As clusters likely formed only a few Gyrs ago, dynamical effects like energy equipartion or dynamical friction are very unlikely to have played any significant role in originating the mass/velocity segregation, especially considering that only a small part of the cluster mass is attached to individual galaxies (\( \leq 15\% \), see G98). If confirmed by a larger sample of real and simulated clusters, the observed segregation of their more massive galaxies would rather be the signature of their hierarchical build–up.

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