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The Fossil Phase in the Life of a Galaxy Group

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ABSTRACT

We investigate the origin and evolution of fossil groups in a concordance LCDM cosmological simulation. We consider haloes with masses between $(1-5)\times10^{13}h^{-1}\mathrm{M}_{\odot}$ and study the physical mechanisms that lead to the formation of the large gap in magnitude between the brightest and the second most bright group member, which is typical for these fossil systems. Fossil groups are found to have high dark matter concentrations, which we can relate to their early formation time. The large magnitude-gaps arise after the groups have build up half of their final mass, due to merging of massive group members. We show that the existence of fossil systems is primarily driven by the relatively early infall of massive satellites, and that we do not find a strong environmental dependence for these systems. In addition, we find tentative evidence for fossil group satellites falling in on orbits with typically lower angular momentum, which might lead to a more efficient merger onto the host. We find a population of groups at higher redshifts that go through a "fossil phase": a stage where they show a large magnitude-gap, which is terminated by renewed infall from their environment.

Key words: galaxies: formation - galaxies : clusters - cosmology : dark matter - galaxies : evolution - methods : N-body simulations

1 INTRODUCTION

Observations in the last decade revealed the existence of groups of galaxies containing extended X-ray-emitting hot gas with properties expected for poor clusters such as the Virgo cluster, but in the optical light completely dominated by a single luminous, giant elliptical galaxy (Ponman et al. 1994; Vikhlinin et al. 1999). The second brightest galaxy in these systems is more than a factor five less luminous than the dominant elliptical.

To be specific, these systems are defined as spatially extended X-ray sources with luminosities $L_{\mathrm{X,bol}} \geqslant 10^{42}h_{50}$ ergs^{-1}. The optical counterparts are galaxy groups with $\Delta m_{12} \geqslant 2$ mag, where Δm_{12} is the absolute R-band magnitude-gap between the brightest and second-brightest galaxies.

These systems are extremely interesting for several reasons: Although they have X-ray temperatures comparable to the Virgo cluster these systems show a galaxy luminosity function with a deficit of bright galaxies beyond the characteristic magnitude of the Schechter function M* , or of visible galaxies as compared to the predictions of cosmological simulations (D'Onghia & Lake 2004), whereas Virgo contains six M* galaxies (Jones et al. 2000). Therefore they have been interpreted as the final outcome of galaxy-galaxy mergers. Numerical simulations suggest that the luminous galaxies in a group will eventually merge to form a single giant elliptical galaxy (e.g. Barnes 1989). The merging timescales for the brightest group members (with magnitudes M $\sim$ M* or brighter) in compact groups are typically a few tenths of a Hubble time. Therefore, by the present day several group galaxies have likely merged into the giant elliptical. Outside of the high-density core, the cooling time for the intra-group medium is larger than a Hubble time; thus, while the luminous galaxies in some groups have had enough time to merge into a single object, the large-scale X-ray halo of the original groups should remain intact. This means that a merged group might appear today as an isolated elliptical galaxy with a group-like X-ray halo (Ponman & Bertram 1993). Hence these systems have been termed "fossil" groups.

Using the ROSAT All-Sky Survey data, Ponman et al. (1994) found the first "fossil" group candidate. The

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RXJ1340.6+4018 system has an X-ray luminosity comparable to a group, but 70% of the optical light comes from a single elliptical galaxy (Jones et al. 2000). The galaxy luminosity function of RXJ1340.6+4018 indicates a deficit of galaxies at the characteristic magnitude M*. Jones et al. (2000) have studied the central galaxy in detail and found no evidence for spectral features implying recent star formation, which indicates the last major merger occurred at least several Gyrs ago.

These systems are not rare. With a number density of $(5 \times 10^{-7} - 2 \times 10^{-6})$ $h^3\mathrm{Mpc}^{-3}$, they constitute 10 to 20 per cent of all clusters and groups with an X-ray luminosity greater than $2.5 \times 10^{42} h$ ergs s^{-1} (Vikhlinin et al. 1999; Romer et al. 2000; Jones et al. 2003). The number density of fossil groups is comparable to that of brightest cluster galaxies (Jones et al. 2003). Thus they may be of considerable importance as the place of formation of a significant fraction of all giant ellipticals.

So far different approaches to model and measure the number density of fossil systems have been undertaken. Milosavljević et al. (2006) adopted an extended Press-Schechter approach to estimate (5-40)% for the expected fraction of fossil groups in a mass range of $10^{13} - 10^{14} h^{-1}\mathrm{M}_{\odot}$ and decreasing to (1-3)% for massive clusters. Recently van den Bosch et al. (2007) used 2dF data to measure a fossil fraction of 6.5 % for group with masses $10^{13} - 10^{14} h^{-1}\mathrm{M}_{\odot}$. Using N-body simulations D'Onghia et al. (2007) estimated a fraction of 18% and Sales et al. (2007) (8-10)% for $M_{\mathrm{group}} > 10^{13} h^{-1}\mathrm{M}_{\odot}$ based on an analyses of the Millennium simulation (Springel et al. 2005). A compilation of measurements of the fossil fraction and a discussion of differences due to selection effects is given in Dariush et al. (2007). Note, however, that some of these systems seem to be fossil clusters rather than fossil groups (Gastaldello et al. 2007; Cypriano et al. 2006, Zibetti et 2007, in preparation), i.e. galaxy clusters with the typical magnitude-gap of 2 between the brightest and the second brightest cluster galaxy. It seems at least that a significant fraction of groups is fossil and it is a strong function of group mass (Milosavljević et al. 2006; Sales et al. 2007; van den Bosch et al. 2007) .

Most of the theoretical work on fossil groups focused on the predictions of the statistics of the magnitude-gap in the luminosity function. The physical processes that lead to the formation of a mass or magnitude-gap in these systems are still poorly understood. Early work suggested that fossil groups result from mergers of the largest galaxies within compact groups (Barnes 1989) and are due to early formation time (D'Onghia et al. 2005; Dariush et al. 2007). However, it is not yet understood under which conditions mergers are so efficient that they produce such an extreme gap in magnitude. When do fossil groups typically form their magnitude-gap? Are fossil systems isolated systems or can they also populate high density regions like galaxy clusters? Are fossil systems early formed systems, are they more concentrated than other systems? Are fossil groups long lasting systems, or does the group environment regulate its lifetime by infall of new massive structures?

These are the open questions which we address here using a high-resolution N-body simulation. The answers should guide the interpretation of observational datasets especially by surveys like PANSTARS combined with COSMOz that can search for fossil systems at higher redshift and provide a framework for understanding the formation of giant ellipticals within the current cosmology.

This paper is organized as follows. We describe the numerical simulation in §2.1 and the selection criterion of the sample of fossil groups in §2.2.

In §3 we describe the fossil group properties we find, like number density, formation time, concentration and time of last major merger. We investigate the formation mechanisms leading to the large magnitude-gap in §4. Our main results are summarized in §5.

2 METHODS

We have selected our sample of fossil groups from a 80 h^{-1}Mpc dark matter only N-body simulation which is large enough to lead to a statistically meaningful sample. Since we are mainly interested in the dynamical properties of the massive group members, we focus on a dark matter simulation in this work.

2.1 Simulation

The initial conditions were generated for a WMAP3 cosmology with matter density $\Omega_{\mathrm{m}} = 0.24$, an linear mass variance on 8 h^{-1}Mpc-scale $\sigma_8 = 0.76$, a dimensionless Hubble parameter $h = 0.73$ and a spectral index of primordial density perturbations $n = 0.96$ (Spergel et al. 2007). We used $N = 512^3$ dark matter particles, i.e. a particle mass of $4 \times 10^8 h^{-1}\mathrm{M}_{\odot}$. Starting at redshift $z = 40$ we evolved the simulation until the presence with the MPI version of the Adaptive Refinement Tree (ART) code (Kravtsov et al. 1997). The ART code enabled us to reach a force-resolution of $1 - 3$ kpc in the most refined regions, making sure our massive sub-haloes do not suffer from over-merging (Klypin et al. 1999) inside of our group sized haloes.

We identified groups with a friend-of-friends (FOF) algorithm with a linking length of $l = 0.17\, d$ (corresponding to a mean over-density of roughly 330), with d the mean interparticle distance. The advantage is that it identifies groups of any shape. In a second step we identified the bound (sub-)structures in the groups. To this end we used the Bound Density Maximum (BDM) halo finder (Klypin et al. 1999). This algorithm removes unbound particles from the haloes and is therefore particularly suitable to identify sub-haloes and their properties, like their circular velocity. Since the determination of sub-halo masses in groups is uncertain we characterized them by their maximum circular velocity. The BDM halo with the highest circular velocity within the FOF group is considered the host group halo. We found 116 groups in the mass range of $(1 \times 10^{13} - 5 \times 10^{13}) h^{-1}\mathrm{M}_{\odot}$, corresponding to the massive end of galaxy groups.

We calculated the mass accretion histories of the haloes using 130 time steps of equal distance in the expansion parameter, $\Delta a = 0.006$. To this end we selected the 20 per cent of the most bound particles of haloes and compare them in 8 consecutive time steps. We uniquely associated a halo to its progenitor by considering halo pairs, which have the largest number of particles in common and do not differ by more than a factor 5 in mass. The last criterion was included to avoid spurious misidentification by sub-haloes with their host halo.

2.2 Selection of Fossil Groups

Fossil groups are defined on the basis of a measured magnitude-gap between the brightest and the second brightest group member. In our simulation we can only identify the dark matter haloes which host the group galaxies. Currently methods are being developed in order to relate galaxy luminosities to dark matter haloes in a statistical way (e. g. Yang et al. 2004; Vale & Ostriker 2004; Cooray & Milosavljević 2005; Conroy et al. 2006). Here we follow this idea and associate luminosities to the (sub-)haloes in the group. We assume simply that the most luminous galaxy is the central galaxy of the group host halo with circular velocity $v_{circ,1}$. Consequently, the halo with the second highest circular velocity $v_{circ,2}$ will host the second brightest group galaxy. Here the circular velocity v_{circ} is always taken at the maximum of the rotation curve.

To model the magnitude-gap we adopt a similar approach as Milosavljević et al. (2006) where we relate the the halo circular velocity to the luminosity of the central galaxy using an empirically measured mean R-band mass-to-light ratio (Cooray & Milosavljević 2005). Assuming a Sheth-Thormen (Sheth & Tormen 1999) mass distribution function for the dark matter haloes and a functional form as in Equation 1, that expresses the halo mass in luminosity for the central galaxies, Cooray & Milosavljević (2005) fit the measured R-band luminosity function of Seljak et al. (2005). We convert our circular velocities to luminosities by the relation

$$L\left(M\right) = L_0 \left(\frac{M}{M_0}\right)^a \left[b + \left(\frac{M}{M_0}\right)^{cd}\right]^{-1/d} \quad (1)$$

with $L_0 = 5.7 \times 10^9 L_\odot$, $M_0 = 2 \times 10^{11}\mathrm{M}_\odot$, $a = 4$, $b = 0.57$, $c = 3.78$, $d = 0.23$, where we substitute circular velocities for masses using the relation found by Bullock et al. (2001): $M/\left(h^{-1}\ \mathrm{M}_\odot\right) = 10^\alpha \cdot [\mathrm{v_{circ}}/\left(\mathrm{km\ s^{-1}}\right)]^\beta$, with $\alpha = 4.3$ and $\beta = 3.4$. We then define fossil groups as having masses in the range of $(1 \times 10^{13} - 5 \times 10^{13})h^{-1}\mathrm{M}_\odot$ and a magnitude-gap $\Delta m_{12} \geqslant 2$ mag in the R-band .

Mass accretion onto haloes stops at the time when they become sub-halos of a more massive object like a group. After infall they start to lose matter due to tidal interactions. Since baryons tend to lie deeper in the potential well, they will be less prone to get tidally stripped. Therefore, the total luminosity is more likely to be related to the mass at infall (see e. g. Kravtsov et al. 2004). Following this idea we characterize the sub-haloes of the groups by their masses and circular velocities *at infall times* onto the group. The choice of relating luminosities to the circular velocities of halos at infall time has been motivated by recent successes in matching the data by modeling the two- and three-point correlation functions (Conroy et al. 2006; Berrier et al. 2006; Marin et al. 2007).

3 DISTRIBUTION AND PROPERTIES OF FOSSIL GROUPS

3.1 Abundance

In this section our main aim is to characterize the properties of the fossil groups of our group sample in order to guide the interpretation of future observational constraints. We begin by computing the abundance of fossil systems in our catalog.

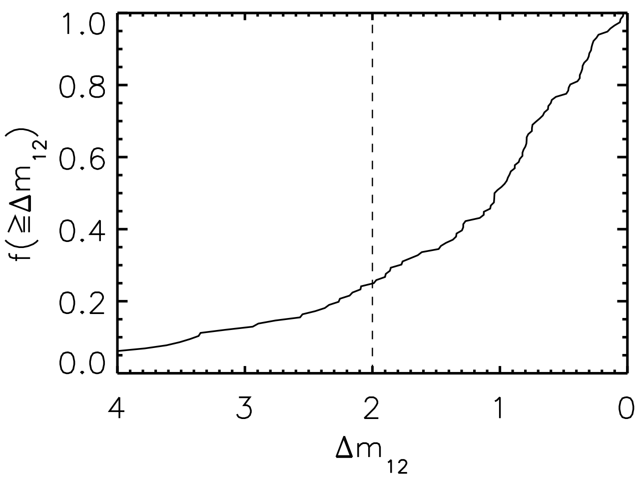

Figure 1. The fraction of galaxy-group sized haloes with a magnitude-gap parameter larger than Δm_{12}. The dashed line indicates our defining magnitude-gap for fossil groups $\Delta m_{12} \geqslant 2$.

Assuming a magnitude-gap of $\Delta m_{12} \geqslant 2$ (see dashed line in Figure 1) 24 per cent of the groups of our catalog are classified as fossil, corresponding to a number density of $5.5\times 10^{-5}h^3\mathrm{Mpc}^{-3}$. This rate is higher than previous estimates based on N-body simulations (D'Onghia et al. 2007), semi-analytic models (Sales et al. 2007; Dariush et al. 2007), and observational estimates (Vikhlinin et al. 1999; Romer et al. 2000; Jones et al. 2003; van den Bosch et al. 2007), which all get a fraction of around 10 per cent for groups in the mass range considered here. However, only 15 well studied fossil groups are known at present with X-ray data. Therefore these abundances present large uncertainties and might be well underestimated. We believe that the over-estimate comes from our adopted scheme for relating circular velocities to luminosities of the central galaxies in groups, where we followed Milosavljević et al. (2006) and Bullock et al. (2001). We are interested mainly in the formation process of systems with a large magnitude-gap, which clearly corresponds to systems with a large gap in circular velocities even if the related magnitudes are uncertain. We therefore stick to our adopted method and study how our selected fossil population differs from the normal group population.

3.2 Environment Density Dependence

Fossil groups are systems with many properties typical for galaxy clusters. Hence, a further interesting test concerns the question whether fossil groups are isolated systems that populate the low density regions or tend to reside in higher density regions of the Universe like galaxy clusters. A good test would be the cross-correlate the X-ray emitting fossil groups with galaxies in the nearby universe, e.g with SDSS data. However the limited number of fossil groups actually known makes an estimate of such correlations extremely difficult. Some observational indications, though still uncer-

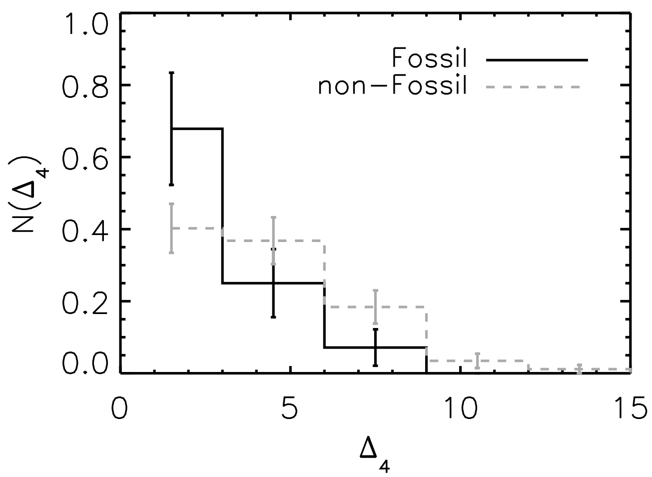

Figure 2. The group environment over-density Δ_4 computed in a sphere of $4h^{-1}$Mpc for fossil (black solid line) and non-fossil groups (grey dashed line). To compute the over-density, the inner virial radius was subtracted. For comparison, cluster typically populate regions of $\Delta_4 > 10$. There does not seem to be a strong tendency for fossil groups to be in low density environments. Error bars indicate 1σ Poissonian uncertainties.

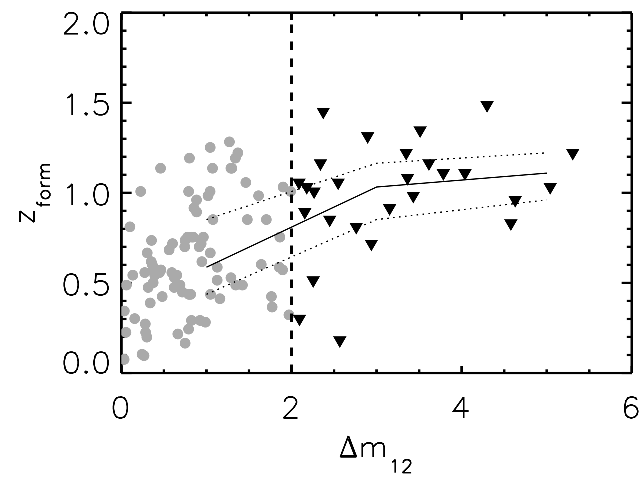

Figure 3. The correlation between the formation redshift of the group host halo and its magnitude-gap parameter for fossil groups (triangles) and normal groups (circles). Over-plotted are the mean values (solid line)and lower and upper quartiles (dotted lines).

tain, would suggest that fossil groups could be fairly isolated systems (e.g. Jones et al. 2000, 2003; Adami et al. 2007).

We check in our simulated sample of groups whether fossil systems populate preferentially low density regions in the universe. We estimate the environmental density on a scale of 4 h^{-1}Mpc . To this end we determine the environmental over-density $\Delta_4 = \rho_4/\rho_{\rm bg} - 1$, where ρ_4 is the dark matter density within 4 h^{-1}Mpc from the group center of mass, with the inner one virial radius is subtracted, and $\rho_{\rm bg}$ is the background matter density. Figure 2 shows the distribution of the over-density Δ_4 for fossil and normal groups. Most of the groups, in the range of mass considered here, independent of being fossil or not, populate preferentially the intermediate over-density region. A two-sided Kolmogorov-Smirnov test for the two cumulative distributions shown gives $D = 0.31$, corresponding to a probability of 0.03 that the the two samples are drawn from the same distribution. We checked that adopting a slightly larger or smaller volume (scales of 2-5 h^{-1}Mpc) does not change our results significantly. We do not find a strong tendency for fossil systems to be preferentially located in low density environments. We suggest therefore that observations might be biased to find fossil groups preferentially in low density regions, which could be due to group selection effects.

3.3 Formation Time

The halo formation redshift is defined as the epoch at which the system assembled 50% of its final mass (e.g. Lacey & Cole 1993). Figure 2 shows a correlation between the magnitude-gap parameter and the formation redshift of the host halo for all the fossil systems (triangles) and the normal groups (grey circles). As already pointed out in D'Onghia et al. (2005, 2007) this correlation shows that fossil groups tend to form earlier than normal groups, albeit with large scatter. In order to assess this correlation we draw the mean and upper and lower quartiles (the solid and dotted lines in Figure 2). The visual impression is quantified by statistical measures as the Pearson's linear correlation coefficient $r = 0.39$, implying a weak linear correlation between the magnitude-gap and the formation time.

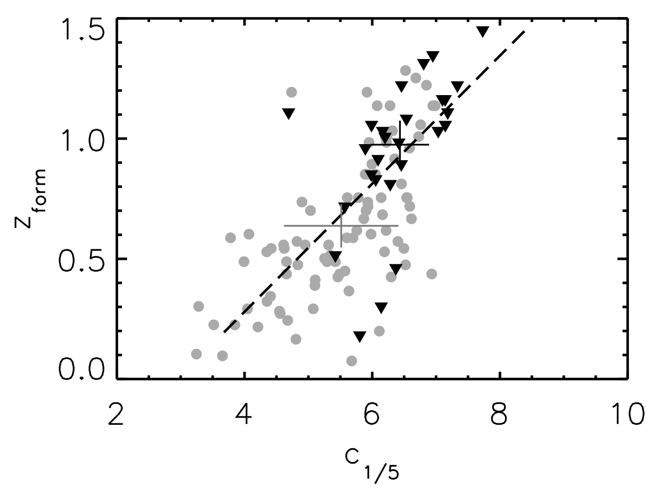

Figure 4. The formation redshift of the host halo as a function of the group concentration. The fossil group sample is marked with triangles and the normal groups are drawn with circles. The dashed line is a linear fit to all points. Crosses correspond to the mean values for the concentrations of fossil: $c_{1/5} = 6.4$ (bold cross) and non-fossil groups $c_{1/5} = 5.5$ (light cross), with the widths indicating the 1σ standard deviations.

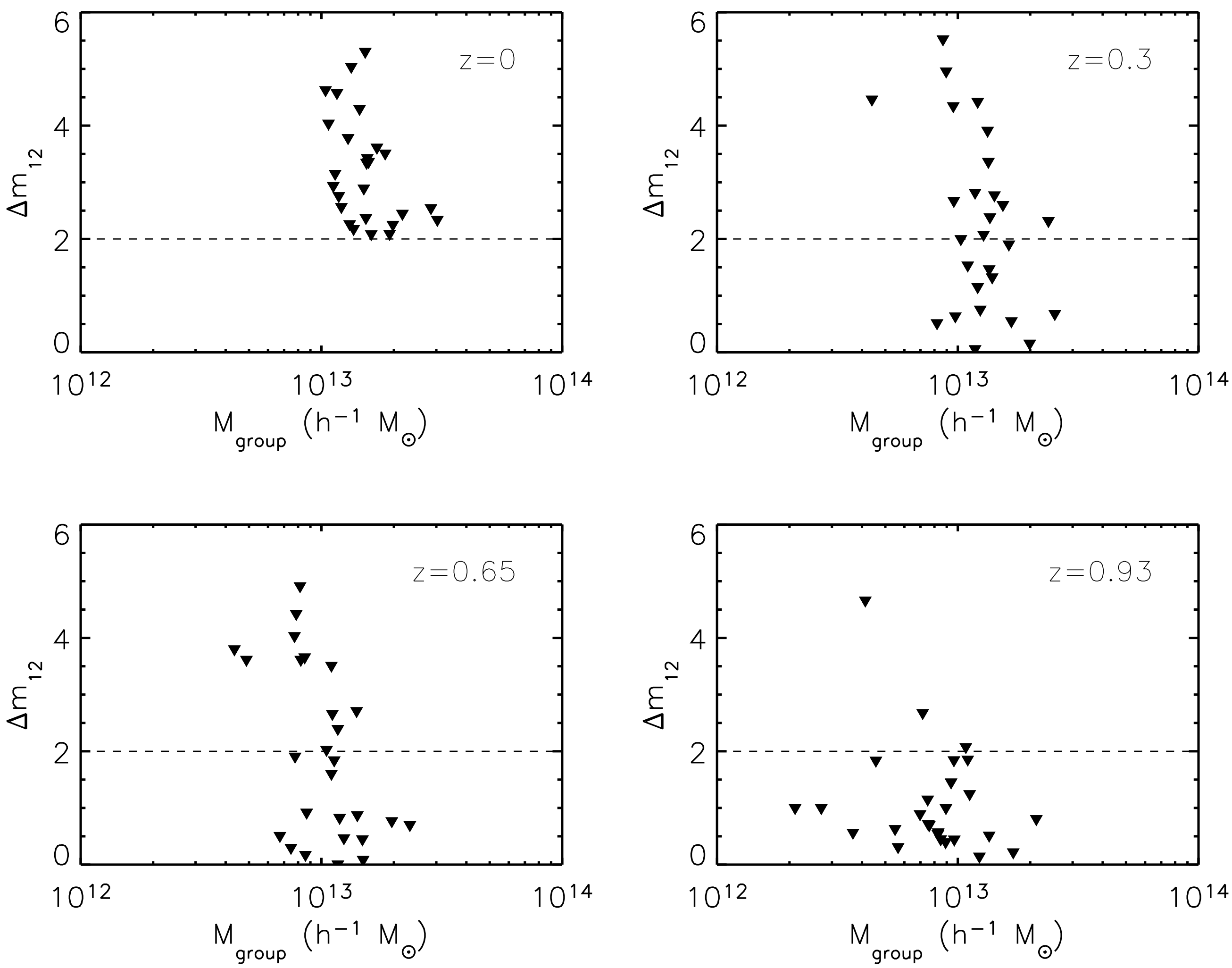

Figure 5. The evolution of the magnitude-gap parameter Δm_{12} for fossil groups selected at z=0 (for redshifts z=0, 0.3, 0.65, and 0.93). The non-fossil groups, which constitute the majority of the groups, are left out from this plot for clarity. The plot shows that the majority of the fossil systems had one or more massive satellites at higher redshift. Note that the formation of the magnitude-gap happens typically later (between $z = 0 - 0.7$) than the formation of the groups, which occurred around $z \geqslant 0.8$ (see Figure 2).

3.3.1 Concentration Parameter

The early formation redshift is also reflected in a higher concentration parameter (Navarro et al. 1997).

We define the concentration of our haloes by the ratio of the virial radius of the host halo to the radius of a sphere enclosing one fifth of its virial mass: $c_{1/5} = r_{\rm vir}/r_{1/5}$. This definition of the halo concentration allows for a robust concentration determination when the haloes are merger remnants and un-relaxed (Avila-Reese et al. 2005). The correlation shown in Figure 3 between formation redshift and concentration is well fitted by a linear relation $z_{\rm form} = -0.79 + 0.27 \times c_{1/5}$ (marked with the dashed bold line).

The fossil groups clearly populate the early formed, more concentrated part of the plot, and have a mean concentration of $c_{1/5} = 6.4$, which is about 16 per cent higher than the concentrations found for normal groups $c_{1/5} = 5.5$. Our findings are consistent with fossil groups being systems with higher dark matter concentrations than usual groups, which supports such a trend found by Khosroshahi et al. (2007). At present there are yet few observational constraints on this issue (e.g. Gastaldello et al. 2007; Khosroshahi et al. 2007). However with the upcoming X-ray observations of fossil groups with Chandra and XMM will provide soon better constraints.

3.4 Last Major Merger

Recent studies of the giant elliptical at the center of fossil groups report no signs of a recent major merger activity, indicating that any major merger should have happened at least more than approximately 3 Gyrs ago (Jones et al. 2000; Khosroshahi et al. 2006).

For each halo we estimate the time of the last major merger of the group haloes of our sample by studying the detailed mass assembly history. To identify the time of the

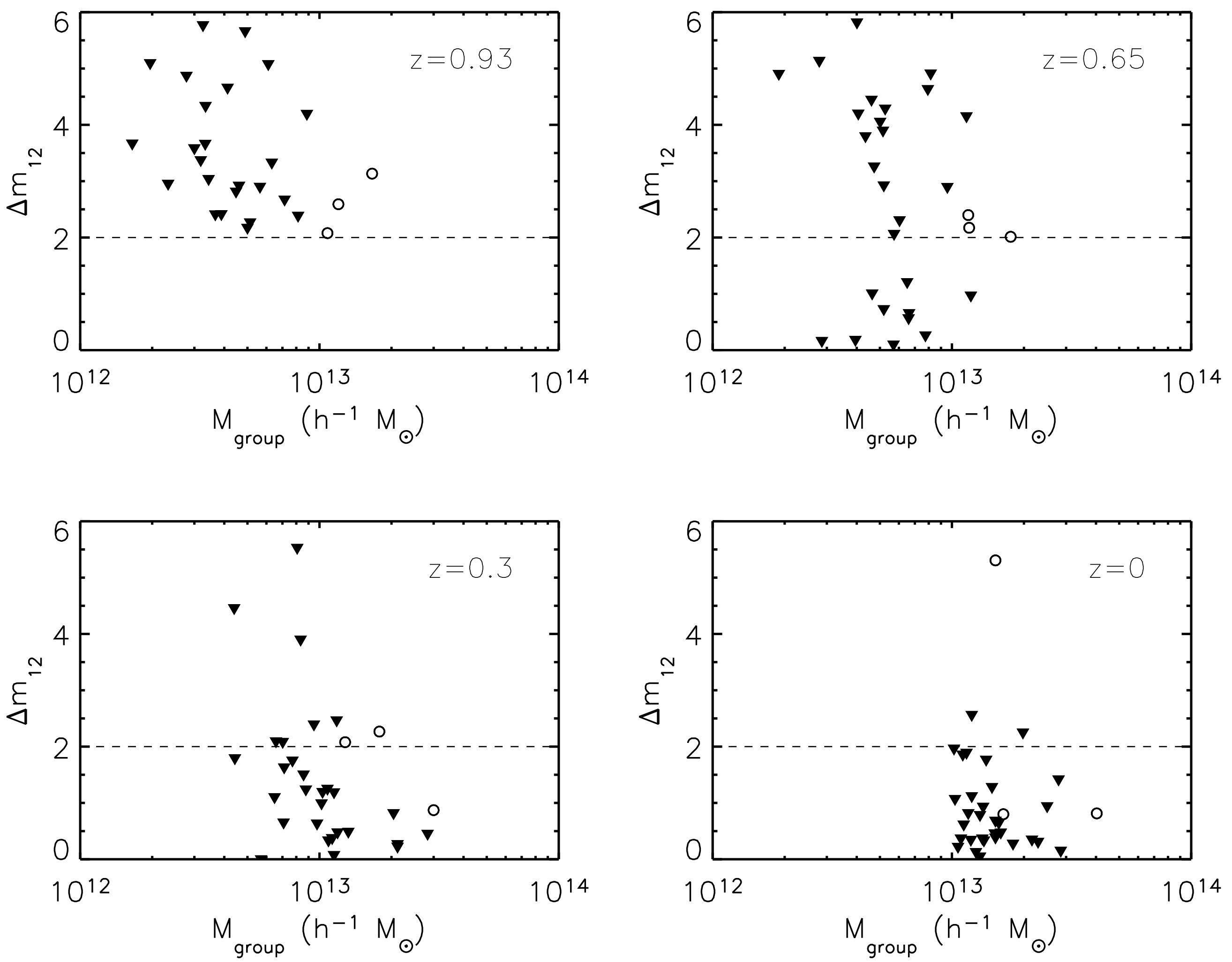

Figure 6. The evolution of the magnitude-gap parameter Δm_{12} for fossil groups selected at z=0.93 that end up in the z=0 group sample, given at different epochs (z=0.93, 0.65, 0.3, and 0). Again for clarity, only the selected sample at z=0.93 is shown. The open circles indicate fossil groups that are selected in the same mass range as the group sample at z=0. Most of the high redshift fossil systems, when traced forward in time, experience renewed infall of massive satellites and become normal groups at z=0. These systems are undergoing a 'fossil phase'.

last major merger, we denote a halo as a major merger remnant if its major progenitors were classified as a single group at one time but two separate groups with a mass ratio less than 4:1 at the preceeding time. Note that when the mass ratio defining the major merger event is restricted to almost 1:1 progenitors, the time of the last major merger should in general coincide with the formation time (as defined above). We find that only 15% of the fossil groups experienced the last major merger less than 2 Gyrs ago, and at least 50% had the last major merger longer than 6 Gyrs in qualitative agreement with the observations.

4 FORMATION OF FOSSIL GROUPS

In previous sections we investigated some properties of our galaxy-group sized haloes that can be compared to observations. In particular, the fossil groups appear to be more concentrated systems, they formed earlier, with the last major merger happened a long time ago, in qualitative agreement with current observational constraints. We now turn to the question why these systems are devoid of a significant substructure. Obviously, no large satellite has fallen in lately. The question then is, how long is such a major infall ago – if it ever occurred? And if they fell in, when do they merge to create the magnitude-gap?

Furthermore, we look for signs of efficient merging in fossil systems. We focus on two main conditions that lead to the formation of these systems: i) the low infall rate of massive satellites into the host halo; and ii) distribution of angular momentum of the in-falling massive satellites.

4.1 Forming the Magnitude-Gap

To quantify when the magnitude-gap was formed in fossil systems, we plot the distribution of the magnitude-gap of fossil groups selected at $z = 0$ in Figure 5. This sample is traced backward in time to $z = 0.3$ (the right top panel); $z = 0.65$ (the bottom panel on the left) and $z = 0.93$ (the bottom panel on the right). We find that the groups selected as fossil at present, show a lower magnitude-gap once traced backwards in time. They therefore do not qualify anymore as fossil systems at higher redshifts. The magnitude-gap is typically formed over a wide range of redshifts between $z = 0 - 0.7$. It worth noting that this happens typically after the group halo has gained half of its mass, which occurred earlier around redshift $z \geqslant 0.8$ (see Fig. 2).

4.2 The Fossil Phase

Is the 'fossil stage' a final stage or will the systems fill their magnitude-gap with the time? To assess this question, we select a sample of fossil systems at high redshift $z = 0.93$, and track these forward in time (as shown in Figure 6). The open circles indicate massive fossil groups in the same mass regime as the sample selected at $z = 0$. Following all the fossil systems forward in time we note that they leave the range where they would be identified as fossil systems due to new in-falling satellites. Only three of these systems did not experience further infall of a massive satellites from their surrounding environment so that they end up as a fossil system today.

Our simulation suggest that the existence of a gap in the galaxy luminosity function in fossil systems is only a transition phase in the evolution of groups, the duration of which is related to the merging of group members with the central object and infall of new haloes.

4.3 Properties of In-falling Satellites

We showed in previous sections that fossil groups tend to assemble earlier their mass than normal groups, and that the unusual magnitude-gap is a transient phase in the evolution of the group in the hierarchical universe. A group identified as fossil today did not experience any late infall of massive satellites to fill the gap in the magnitude distribution function of the group members. In order to assess this question quantitatively we compute the average infall rate of haloes onto fossil systems as compared to normal groups. This quantity is expressed in our analysis by computing the cumulative number of massive (within 2 magnitudes of the host) satellites falling into the host halo after redshift z divided by the total number of fossil (normal) groups: $< N_{\rm infall}(< z) >= N_{\rm infall}(< z)/N_{\rm groups}$. Figure 7 shows that fossil groups accrete the larger satellites earlier in time as compared to the normal groups. An early infall of massive companions ensures enough time for the massive satellite to merge into the host halo. Note that for $z > 0.8$ fossil and non-fossil groups have similar infall history of massive satellites. In fact the slopes of the evolution of the infall rate is the same for both distribution for $z > 0.8$, showing that the infall rate of satellites is only different at low redshifts.

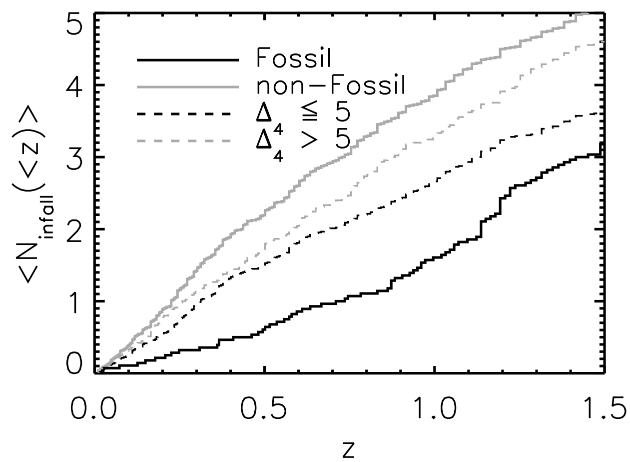

Figure 7. The mean cumulative number of massive satellites with $\Delta m_{12} < 2$ mag in-falling into the host halo at redshifts $z_{\rm infall} < z$. The grey solid line corresponds to normal groups and the black solid line to fossil groups. The dashed curves indicate the mean cumulative number of massive satellites when the group samples are split up by low dense regions $\Delta_4 \leqslant 5$ and higher dense regions $\Delta_4 > 5$.

We checked whether the difference in infall rate is determined by environment. This is done by splitting the sample up in $\Delta_4 < 5$ and $\Delta_4 \geqslant 5$ and evaluating the cumulative number of in-falling satellites (see dashed lines in figure 7). Although the denser regions do experience a bit more infall, the difference is only of the order of 10-30 per cent, not as big as we observe for fossil and non-fossil systems (in agreement with Maulbetsch et al. (2007), who find little environmental dependence of the mass accretion history in this mass range). This supports lack of a strong environmental preference for fossil groups found in section 3.2.

We address the question whether the conditions under which the massive satellites enter the group enable an efficient merger which could lead to a gap in the magnitude distribution of the fossil group galaxies. We checked the angular momenta values of the satellites at time of infall. Figure 8 shows the angular momentum of the satellites at infall time. The angular momentum is calculated by taking the cross product of the distance at infall and the velocity at infall $L_{\rm sat} = (\mathbf{r}_{\rm inf} \times \mathbf{v}_{\rm inf}) / (r_{\rm max} \cdot {\rm v}_{\rm circ})$, with $r_{\rm max}$ and ${\rm v}_{\rm circ}$ both measured at the maximum of the rotation curve. Both distributions peak at $L_{\rm sat} \approx r_{\rm max}{\rm v}_{\rm circ}$. Fossil groups seems to be lacking satellites in the high end tail of angular momentum distribution, which may cause a faster merging of the satellites. However, since the distribution is rather poorly sampled, better number statistics are needed to confirm this result.

5 SUMMARY AND CONCLUSIONS

From an N-body simulation, we select and analyze a large sample of galaxy group-sized haloes, that allows us to study in detail the mechanisms that lead to the formation of fossil systems in the hierarchical universe.

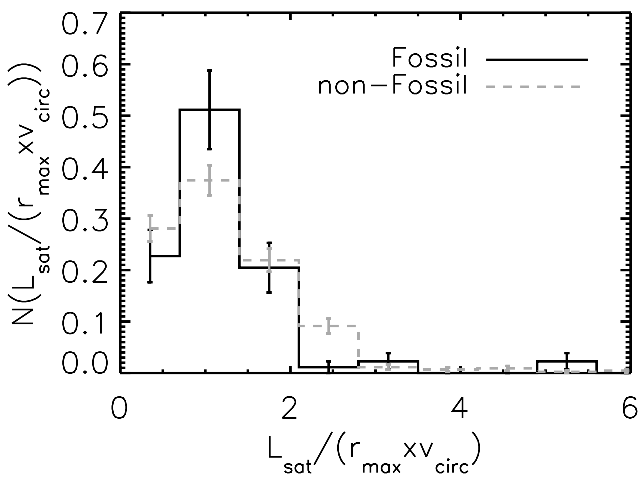

Figure 8. The distribution of the in-falling satellite normalized angular momentum for fossil (black solid line) and non-fossil groups (grey dashed line). The distribution seems more narrowly distributed around $L_{\rm sat} \approx r_{\rm max}{\rm v}_{\rm circ}$ for fossil groups, i.e. its high angular momentum tail seems to be less pronounced. Error bars indicate 1σ Poissonian uncertainties.

Our criterion to select fossil systems is based on identifying galaxy-group sized haloes showing a gap in the magnitude between the two most massive members. This selection criterion assumes that the circular velocity of a halo traces its luminosity until it becomes a substructure of another more massive system. We relate the magnitude of our haloes to the circular velocities by using the empirical mean relation between dark matter halo mass and central galaxy R-band luminosity found by Cooray & Milosavljević (2005).

Our results may be summarized as follows:

• In the mass range $1 \times 10^{13} - 5 \times 10^{13} h^{-1}{\rm M}_{\odot}$ 28 of the 116 groups sized haloes, i. e. 24 per cent qualify as fossil groups according to the definition of a magnitude-gap of 2 magnitudes between the brightest and second most bright galaxy. This fraction is higher than the measured values. The largest uncertainty here is how to relate the mass or circular velocity of the haloes to the luminosities of their central galaxies. Because our adopted method of relating mass to galaxy luminosity is uncertain due to the broad scatter in this relation (Cooray 2006), and the rate is sensitive to the group definition, as well as selection effects, a robust comparison to observed number densities obtained by other authors is difficult at the moment. We are selecting systems with large circular velocity- or respectively mass-gaps, so that our sample can be used to study the formation of the extreme magnitude-gaps observed in fossil systems.

• The fossil groups identified in our sample tend to form earlier than the other groups. The fossil systems have assembled half of their final mass around $z \geqslant 0.8$ in agreement with the previous works. They form their magnitude-gap typically between redshift $z = 0 - 0.7$, much later than the formation time of the groups. The early formation time is also expressed in a slightly higher dark matter concentration. The average concentration for the fossil groups is $c = 6.4$ compared to $c = 5.5$ of normal groups. Further, we find that the majority of the fossil group seem to have experienced the last major merger longer than 3 Gyr ago.

• We do not find a strong correlation between the environment and the formation of fossil systems. Observations that indicate that fossil systems are found preferentially in low density environments might be biased by selection effects.

• The primary driver for the large magnitude-gap is the early infall of massive satellites that is related to the early formation time of these systems. The difference in infall rate for different group environments is only of order 10-30 per cent, far less than the observed difference between fossil and non-fossil groups, and hence the current environment does not seem the primary driver for the lack of massive satellites. This is in agreement also with the lack of strong correlation between fossil systems and environment.

• We suggest that efficient mergers of massive members within the groups can create the magnitude-gap typical of fossil groups at any redshift. The efficiency of the merger process seems to be linked to the lower angular momentum of the massive satellites in-falling into the host halo of fossil groups when compared to normal groups. However, due to the limited number statistics we need more data to substantiate this.

• By selecting samples of fossil groups at higher redshift ($z \approx 1$) we find that many of them do not exhibit the magnitude-gap anymore once they are traced forwards until present time. The majority of them fill the magnitude-gap with time by infall of new massive satellites. We conclude that the stage for a group to be "fossil" is a transient phase.

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