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# PROBING GALAXY FORMATION MODELS IN COSMOLOGICAL SIMULATIONS WITH OBSERVATIONS OF GALAXY GROUPS

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## ABSTRACT

We use multi-wavelength observations of galaxy groups to probe the formation models for galaxy formation in cosmological simulations, statistically. The observations include Chandra and XMM-Newton X-ray observations, optical photometry and radio observations at 1.4 GHz and 610 MHz. Using a large sample of galaxy groups observed by the XMM-Newton X-ray telescope as part of the XMM-Large Scale Survey, we carried out a statistical study of the redshift evolution of the luminosity gap for a well defined mass-selected group sample and show the relative success of some of the semi-analytic models in reproducing the observed properties of galaxy groups up to redshift $z \sim 1.2$. The observed trend argues in favour of a stronger evolution of the feedback from active galactic nuclei at $z < 1$ compared to the models. The slope of the relation between the magnitude of the brightest cluster galaxy and the value of the luminosity gap does not evolve with redshift and is well reproduced by the models. We find that the radio power of giant elliptic galaxies residing in galaxy groups with a large luminosity gap are lower compared to giant ellipticals of the same stellar masses but in typical galaxy groups.

*Key words:* Galaxies: Galaxy Groups: Cosmological Simulations

## 1. INTRODUCTION

Galaxy groups are very interesting because they are the seeds for the most massive structures in the Universe, e.g. galaxy clusters, and also because a number of important astrophysical processes that shape the structure of galaxies take place in these environments. Galaxy groups have also been found to form a mixed population of "old" and "young" systems, according to their formation epoch, unlike galaxy clusters which are predominantly young galaxy systems (Raouf et al., 2014). In other words, despite the fact that a large number of galaxy groups are expected to be recently forming, in LCDM cosmology, a number of them survive the hierarchal mergers and appear unaffected by halo mergers over the past few Gyr.

A pioneering study by Ponman et al. (1994) showed that galaxy groups dominated by a single giant elliptical galaxy, some as luminous as brightest cluster galaxies (BCG), have X-ray emission which represents an old population of group halos. This very massive galaxy could have formed by cannibalising the neighbouring galaxies, leaving a large deficiency in the population of the luminous galaxies in groups. These old group halos are conventionally identified as having X-ray luminosities comparable to X-ray bright groups ($L_X \geq 10^{42} ergs^{-1}$) and a large luminosity gap, 2 magnitudes or more, between the first and second ranked galaxies within half the group virial radius (Jones et al., 2003). They have been known since then as fossil groups. The X-ray observations of galaxy groups show that the hot gas is retained during the process of galaxy mergers. Most of these systems have been identified in the local universe and through serendipitous observations. An example of a massive fossil galaxy group is show in Figure 1 in which a luminous elliptical galaxy is surrounded by a Mpc scale hot gas show in blue (Khosroshahi et al. 2004) [1].

There have been many studies focused on the detailed characterisation and properties of fossil groups (Khosroshahi, Jones, & Ponman, 2004; Sun et al., 2004; Khosroshahi, & Ponman, 2006), based on X-ray and optical observations. Khosroshahi, Ponman and Jones (2007) show that for a given optical luminosity, fossil groups are not only more X-ray luminous than the general population of galaxy groups, but they also have a more concentrated halo as well as a hotter IGM for a given halo mass.

Fossil galaxy groups offer the advantage that the brightest group galaxy falls at the centroid of the X-ray emission where catastrophic cooling should occur (Fabian 1994). In addition, fossil dominant galaxies are

[1] European Space Agency press release, http://www.esa.int/Our_Activities/Space_Science/XMM-Newton_digs_into_the_secrets_of_fossil_galaxy_clusters

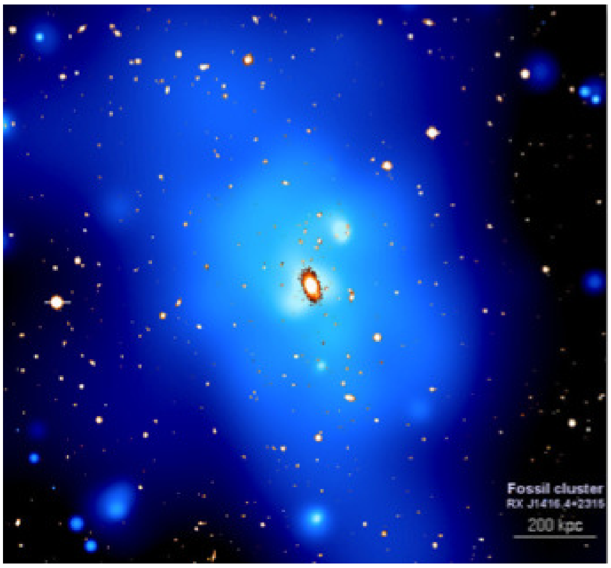


Figure 1. X-ray emission (blue) from the Intergalactic Medium surrounding a giant elliptical galaxy in RX J1416.4+2315, one of the most massive fossil groups known to date.

expected not to have had recent major mergers. The group itself has not experienced any major infall in its recent evolutionary history. As a result fossil groups are ideal laboratories to study both galaxy and IGM properties without possible influences by group or galaxy mergers.

## 2. THE DATA AND THE SIMULATIONS

In our studies we have used XMM-Newton observations of the CFHTLS wide (W1) field as a part of the XMM–LSS survey (Pierre et al., 2007). The optical images were obtained with the MegaPrime instrument mounted on the CFHT in the five filters u*, g′, r′,i′ and z′ (e.g., Erben et al., 2013). We rely on the photometric redshift catalogs of the CFHTLS survey and some spectroscopic observations of VIMOS-VLT Deep Survey (VVDS) (Le Fèvre et al., 2005) and the targeted cluster follow-up of Adami et al. (2011).

We use the Millennium Simulation public dataset (Springel et al., 2005) based on a ΛCDM cosmological model. The simulation box $(500h^{-1}Mpc)^3$ contains $2160^3$ particles and has a mass resolution of 8.6× $10^8$ $h^{-1}$ $M_\odot$. For galaxy models we use various semi-analytic models including those developed by Guo et al. (2011) (Guo11), Bower et al (2006) (B06) and De Lucia and Blaizot (2007) (DLB07). Although all three models are based on the Millennium Dark Matter Simulation, some differences exist between them, such as in their merger trees, AGN feedback efficiency and timing, and tidal disruption. For the study of galaxy luminosity functions we only use the semi-analytic model (SAM) of Guo et al. (2011).

## 3. LUMINOSITY GAP STATISTICS

While earlier studies of the luminosity gap statistics have been limited to the local universe (Smith et al., 2010), we identify 129 X-ray galaxy groups, covering a redshift range $0.04 \geq z \geq 1.23$, selected from the ~3 degree$^2$ part of the CFHTLS W1 field overlapping XMM observations performed under the XMM-Newton Large Scale Survey (XMM-LSS) project (Gozaliasl et al 2014a). These are mostly groups and poor clusters, with masses in the range $10^{13}$ to few $10^{14}$ solar masses.

To test the evolution of properties of galaxy groups in observations and SAMs, we define four subsamples using the following redshift and halo mass ranges:

(S–I) 0.04 <z<0.31 & 13.00< $log(\frac{M_{200}}{M_\odot})$ ≤13.45

(S–II) 0.20<z≤0.45 & 13.45< $log(\frac{M_{200}}{M_\odot})$ ≤14.02

(S–III) 0.45<z≤0.80 & 13.45< $log(\frac{M_{200}}{M_\odot})$ ≤14.02

(S–IV) 0.80<z≤1.10 & 13.45< $log(\frac{M_{200}}{M_\odot})$ ≤14.02

We calculate the magnitude gap between the first and the second brightest galaxies in groups and clusters according to the photometric membership assignment using a two colour red-sequence finding algorithm. For 26 groups in our catalog we calculate the magnitude gap using a spectroscopic membership assignment and for the remaining 102 groups the gaps are calculated using the red-sequence membership assignment.

In Fig.2, we compare the distribution of the magnitude gap between X-ray groups and the predictions of SAMs, G11 , DLB07 and B06. As the completeness limit may affect the magnitude gap calculation of groups with $\Delta$ $M_{1,2}$ > 2 at z>0.5, we define two different bin sizes, with 1 mag for systems with $\Delta M_{1,2}$ <2, while assigning all $\Delta M_{1,2}$ ≥2 groups to a single bin. Such a binning scheme is introduced to remove the effect of completeness on the binned fractions. We use both the formal selection of the subsamples (solid histograms) and modelling of the X-ray selection. For the later, we introduce mass-dependent weights, $\frac{V_{obs}(M_{200},z)}{V_{sim}}$. $V_{obs}$ is the survey volume for detecting groups as a function of $M_{200}$ and z, where $V_{sim}$ is equal to the (500 Mpc $h^{-1})^3$ volume of the Millennium simulation. We evaluate the total number of groups corresponding to each $\Delta M_{1,2}$ bin by summation of the weighted number of groups. We illustrate the resulting constructed model magnitude gap distributions with dashed red (G11), dashed-dotted blue (B06) and dotted green (DBL07) histograms in Fig. 2.

In agreement with the findings of Smith et al. (2010), the fraction of detected groups, $f(\Delta M_{1,2})$, in all histograms of Fig. 2 declines with $\Delta M_{1,2}$. The slope of the relation is shallower for (S–I) compared to other subsamples, indicating a larger contribution of fossil groups. The trends seen in the data for groups and clusters with $\Delta M_{1,2}$ ⩽3 are well reproduced by both DLB07 and G11 models, while the B06 model predicts the slopes that are too steep. In addition, as previously noticed by Dariush et al. (2010), the B06 model over-predicts the fraction of clusters with $\Delta M_{1,2}$ ⩽1 for S-II to S-IV.

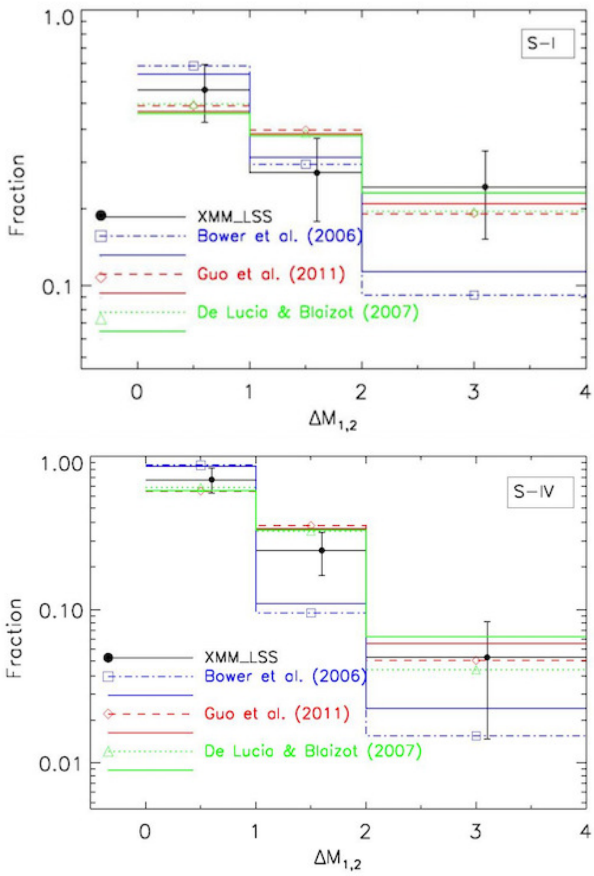


Figure 2. The observed fraction of galaxy groups as a function of their magnitude gap (black points with error bars) compared to the predictions of semi-analytic galaxy formation models, B06 (solid and dashed-dotted blue histograms), DLB07 (solid and dotted green histograms) and G11 (solid and dashed red histograms) for S–I and S–IV. We find that the fraction of groups declines with magnitude gap at all redshifts. Magnitude gap bin sizes are equal to one magnitude for $\Delta M_{1,2}$ <2. $\Delta M_{1,2}$ ≥2 systems are plotted as a 2 magnitude wide bin.

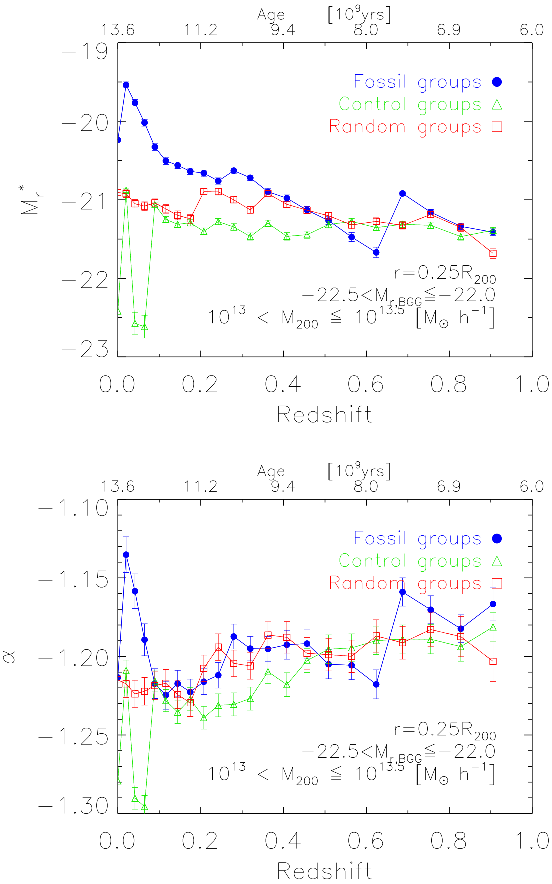


Figure 3. Evolution of $M^*$ and $\alpha$ with redshift and the age of the universe for fossil (blue filled circles), control (green open triangles), and random groups (red open squares) for SI.

We found that $22.2 \pm 6$ of our groups at $z \geq 0.6$ are fossil groups. The observations have also offered unique and powerful probes for the semi-analytic models implemented in the Millennium dark matter simulation up to z=1, for the first time.

## 4. LUMINOSITY FUNCTION

The Canada France Hawaii Telescope Legacy Survey (CFHTLS) optical photometry has already been used to study the galaxy luminosity functions of a small subsample of 14 X-ray selected clusters from the XMM-LSS survey (Alshino et al 2010). Motivated by our findings in this study we studied the evolution of the luminosity function of galaxy groups in fossil and non-fossil groups and also parametrised the luminosity function of the local and high redshift galaxy groups (Gozaliasl et al 2014b) in the cosmological simulations. Using the semi-analytic models based on the Millennium simulation, we back traced the luminosity function of galaxies residing in progenitors of groups classified by the magnitude gap at redshift zero. We determine the luminosity function of galaxies within a quarter, half and the virial radius of galaxy groups/clusters (an example is shown in the figure; the ontrol sample has a small luminosity gap and the random groups represent the general population of the groups in the Millennium simulation for a given halo mass). The bright end of the galaxy luminosity function of fossil groups shows a significant evolution with redshift, with changes of about 1-2 mag between z 0.5 and z=0 within half-virial radius, suggesting that the formation of the most luminous galaxy in a fossil group has had a significant impact on the characteristic (M*) galaxies in the past 5 Gyr. In contrast, the slope of the faint end of the luminosity function shows no sign of a significant redshift evolution and the number of dwarf galaxies in the fossil groups exhibits no evolution, unlike in non-fossil groups where it grows by about 25-40% towards low redshifts.

## 5. FUTURE GALAXY MODELLING; CONSTRAINTS ON AGN ACTIVITIES

In addition to exploring the advantages of the luminosity gap statistics we use GMRT observations of galaxy

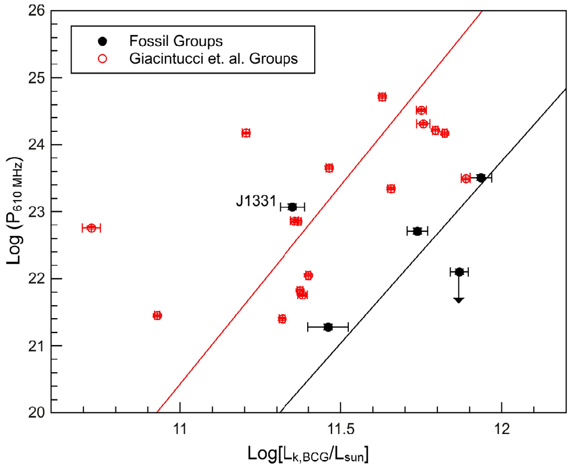


Figure 4. 610 MHz luminosity vs $k$-band BGGs luminosity of fossil galaxy groups (black) and Giacintucci et al. (2011) groups (red). The red and black lines correspond to fits to the red and black samples.

groups to demonstrate that the luminosity gap in groups affects the power of the radio emission in both 21cm and 50 cm radiation, indicating that the AGN activities are affected by galaxy mergers.

IGM heating is one of the challenging issues of the observational cosmology in areas of galaxy groups and clusters. Many galaxy groups and clusters have been found to contain hot intergalactic gas, most of which has a cooling timescale much longer than a Hubble time. The cooling time in the core of many galaxy groups and clusters is shorter than the Hubble time. While it was argued that this gas should cool dramatically to a very low temperatures, a challenge was posed by X-ray observations of the XMM-Newton and the Chandra when they found no evidence of a catastrophic cooling, suggesting that one or more processes are stopping the gas from cooling below a certain temperature (Peterson and Fabian 2006 and reference therein). Active Galactic Nuclei (AGN) are seen as a primary source of heating mainly because they appear to be present in almost all the galaxy groups and clusters, but not necessarily in active form when it is observed. Bubble structures are one of the main supporting evidences for AGN heating as it is discussed in many samples of systems. (Birzan et al., 2004).

Radio observations of all sources were performed by the GMRT (MirAghaee et al 2014). Observing frequencies were chosen to be at 1.4 GHz and 610 MHz with 16 MHz band width in both lower-side band and upper-side band. Except for NGC 6482, the 1.4 GHz information was taken from the VLA archive. For all objects radio emission has been detected which coincides with the corresponding BGG in the optical band and the peak brightness spot of the X-ray emission, except for the source J1552.2+2013. In two cases, ESO 3060170 and J1416, the radio observations show lobes extending up to 4 and 28 kpc from the central source. In particular, the radio lobes are detected clearly in the 610 MHz observations, for both systems.

The power introduced by radio jets for mechanical heating in the sampled objects is not sufficient to suppress the cooling flow. We compare the 1.4 GHz and 610 MHz radio luminosities of fossil groups with a sample of normal galaxy groups of the same radio brightness (BGGs), stellar mass, and total group stellar mass, quantified using the $K$-band luminosity. It appears that the fossil BGGs are under-luminous at 1.4 GHz and 610 MHz for a given BGG stellar mass and luminosity, in comparison to a general population of the groups. In addition, we explore how the bolometric radio luminosity of the fossil sample depends on cluster and group characteristics.

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