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Fossil Systems; a Multi-wavelength Approach towards Understanding Galaxy Formation

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Academic Editors: José Alfonso López Aguerri, Enrichetta Iodice and Alexei Moiseev
Received: 2 November 2015; Accepted: 7 March 2016; Published: 25 March 2016

Abstract: Fossil systems are understood to be the end product of galaxy mergers within groups and clusters. Their halo morphology points to their relaxed/virialised nature, thus allowing them to be employed as observational probes for the evolution of cosmic structures, their thermodynamics and dark matter distribution. Cosmological simulations, and their underlying models, are broadly consistent with the early formation epoch for fossils. In a series of studies we have looked into galaxy properties and intergalactic medium (IGM) in fossils, across a wide range of wavelengths, from X-ray through optical to the radio, to have a better understanding of their nature, the attributed halo age, IGM heating and their AGNs and use them as laboratories to constrain galaxy formation models. Adhering to one of less attended properties of fossils, using the the Millennium Simulation, we combine luminosity gap with luminosity segregation (the brightest galaxy offset from the group luminosity centroid) to identify the most dynamically relaxed galaxy groups which allows us to reveal brand new observational connections between galaxies and their environments.

Keywords: galaxies; galaxy groups; galaxy formation and evolution

1. Introduction

Galaxy groups are important entities not only because the majority of galaxies are in groups but also because they are the seeds for the most massive structures in the Universe and the hosts for a number of important astrophysical processes that shape the structure of galaxies. A pioneering study by Ponman *et al.* [1] showed that galaxy group dominated by a single giant elliptical galaxy, some as luminous as brightest cluster galaxies (BCG), with a groups scale X-ray emission exists which represents a population of group halos which have formed relatively early. As shown in the simulations, this very massive galaxy could form by cannibalising the neighbouring galaxies, leaving a deficiency in the population of the luminous galaxies in the group. 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 magnitude or more, between the first and second ranked galaxies within half the group Virial radius [2] and are 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 such systems have been identified in the local universe and through serendipitous observations.

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 [3]. 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 in the past few Gyr.

Earlier studies of fossil groups focused on the detailed characterisation and properties of fossil groups [4–7], based on X-ray and optical observations. Khosroshahi, Ponman and Jones [8] showed that for a given optical luminosity, fossil groups are not only more X-ray luminous than the general population of galaxy groups, but also have a more concentrated dark matter halo as well as hotter IGM for a given halo mass. Bharadwaj *et al.* [9] showed that fossils are more X-ray luminous for a given X-ray temperature, however they interpreted that as a result of selection effect. They also have indicated that the normalisation of the L_X–T relation is higher for fossils than for non-fossils. A recent study by Kundert *et al.* [10] shows that there is no noticeable difference between fossil and non-fossli systems in scaling relations.

Due to their formation history and degree of virilisation, fossil galaxy groups offer the advantage that the brightest group galaxy (BGG) falls at the centroid of the X-ray emission where the catastrophic cooling should occur. In addition fossil dominant galaxies are expected not to exhibit 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.

In this presentation we go through various aspects of the studies of fossil groups, covering observations and simulations with a focus on the new findings in the last two years and the implications on probing galaxy formation models.

2. Observations

The observational studies of fossil groups owes to ROAST X-ray observations of galaxy groups and clusters [1,2]. Later Chandra and the XMM-Newton observations revealed significant amount of details [4–6]. Most of the studies of fossil groups were limited to the local universe, however, Gozaliasl *et al.* [11], provided a sample which could allow the studies to be conducted at $z \approx 1$. The study used the XMM-Newton observations of the CFHTLS wide (W1) field as a part of the XMM–LSS survey [12]. 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., [13]). The data provided a tool to probe galaxy formation models using the luminosity gap and other stellar properties of galaxies at high redshift.

Most of the studies of fossil groups and clusters have been identified in X-ray surveys. However in a recent study we have taken a different approach by performing a pure optical identification of large luminosity gap groups followed by X-ray observations. Khosroshahi *et al.* [14] reports on the X-ray and optical observations of galaxy groups selected from the 2dfGRS group catalog, to explore the possibility that such galaxy groups can be associated with an extended X-ray emission, similar to that observed in the X-ray selected fossil galaxy groups. The X-ray observations of 4 galaxy groups were carried out with Chandra telescope. Combining the X-ray and the optical observations, we find some evidence for the presence of a diffuse extended X-ray emission beyond the optical size of the brightest group galaxy. The significance of this study lies in the fact that giant elliptical galaxies form in the media in which the hot gas is also heated to an X-ray emitting temperature. Thus a giant elliptical galaxy can not simply form in a monolithic collapse and instead it can only form as part of the process that also shock heats the gas with a cosmic origin. A rough estimation for the comoving number density of fossil groups is obtained to be 4 to 8×10^{-6} Mpc^{-3}, in broad agreement with the estimations from observations of X-ray selected fossils and predictions of cosmological simulations. The results complements the study of Rasmussen *et al.* [15], who used a similar sample selection except for the large luminosity gap and the BGG luminosity, by demonstrating that these two selection criteria can result in detection of the X-ray diffuse emission unlike in their study using the XMM-Newton observations.

Figure 1 shows the smoothed X-ray emission for for 2PIGG 2868 with a clear extended X-ray emission. This extended X-ray halo is not seen for 2PIGG 1404 because the dominant galaxy in this group is not a giant elliptical galaxy.

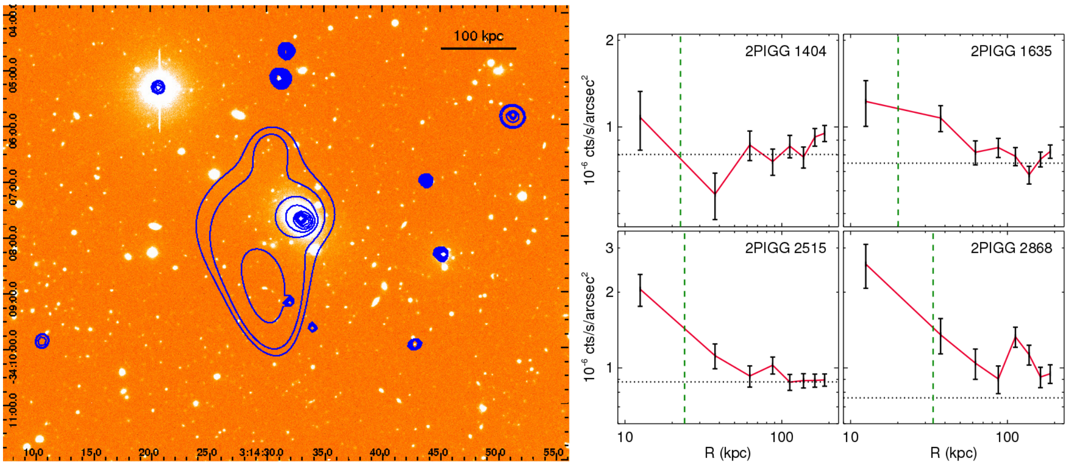

Figure 1. The smoothed X-ray contours over optical R-band images of the central regions for 2PIGG 2868 (**left**) *Chandra* 0.3–2 keV X-ray surface brightness profiles of the groups. The horizontal dotted lines show the background level evaluated from a surrounding annulus in the source data. The vertical dashed lines mark the isophotal radius reaching 25 mag arcsec^{-2} in B-band, e.g., 0.5 D_{25}, for the brightest group galaxy. The X-ray surface brightness extends well beyond the optical size (D_{25}) of the most luminous galaxy in the group with the exception of 2PIGG 1404 (**right**). The plots have been adopted from Khosroshahi *et al.* [14].

The IGM heating is one of the most 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. As we argued in Section 1, Fossil groups are known to have not experienced a major mergers in the past 4 Gyrs [2]. This turns fossils into a simple laboratory to study the IGM heating as they are expected to form strong cool cores unless they are balanced via other heating mechanisms.

Recent GMRT observations of a sample of galaxy groups opened a new window in the studies of fossil galaxy groups allowing these systems to be employed for a better understanding the AGN feedback and its role in the IGM heating in dynamically relaxed galaxy groups. Miraghaei *et al.* [16,17] study the IGM heating in a sample of five fossil galaxy groups by using their radio properties at 610 MHz and 1.4 GHz. The power by radio jets introducing mechanical heating for the sampled objects is found to be insufficient to suppress the cooling flow. Therefore shock heating and conduction, as alternative heating processes have been discussed. Further, the 1.4 GHz and 610 MHz radio luminosities of fossil groups are compared to a sample of normal galaxy groups of the same radio brightest (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 (Figure 2). According to the current AGN fueling scenarios, accretion of cold gas or hot gas can explain the result. Using deep optical (R-band) and near-infrared (Ks-band) data, Khosroshahi, & Ponman [6] showed that BCGs in fossil groups have discy isophotes that implies they have undergone gas rich mergers when their super massive black holes had been fueled via high rate of cold gas accretion. Since then, and probably after quenching of star formation, for about some Gyrs there were no source of cold accretion and the hot intergalactic gas accretion was the only fueling way. The cool core at the center of groups have been formed [9] and the group ended up with less efficient AGN activity because of black hole low accretion rate.

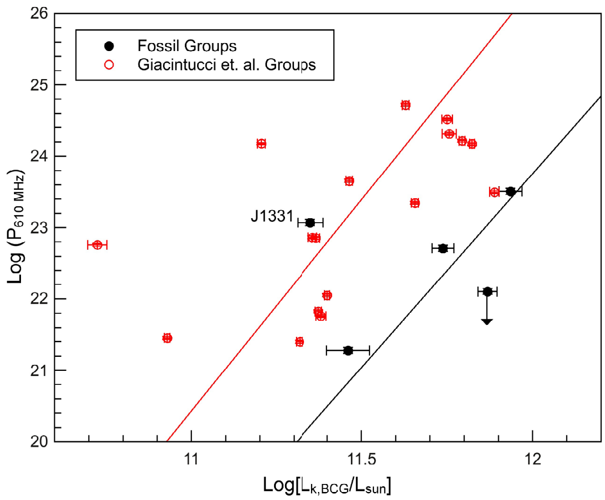

Figure 2. 610 MHz luminosity *vs.* *K*-band Brightest Group Galaxies (BGGs) luminosity of fossil galaxy groups (black) and Giacintucci *et al.* [18] groups (red). The red and black lines correspond to fits to the red and black samples. This plot has been adopted from Miraghaei *et al.* [16].

3. Simulations

Fossil have shown interesting observational properties, some of which are described above. However, they also have become a very useful tools to study and probe galaxy formation models. We use the Millennium Simulation public dataset [19] based on a ΛCDM cosmological model [3]. The simulation box $(500\ h^{-1}Mpc)^3$ contains 2160^3 particles and presents the mass resolution of $8.6 \times 10^8\ \mathrm{h}^{-1}\ \mathrm{M}_\odot$. For galaxy models we use various semi-analytic models including those developed by Guo *et al.* [20]. There are many more such models based upon the Millennium Dark Matter Simulation, however, some differences exist between them such as in their merger trees, AGN feedback efficiency and timing, tidal disruption.

Following D'Onghia *et al.* [21], Dariush *et al.* [22] used the Millennium simulations to show that fossil groups represent older halos than the halos in which the luminosity gap is small ($\Delta m_{12} \leq 0.5$). As a definition ([22]), a galaxy group which formed more than 50 per cent of its total mass by $z \approx 1$ is labled as old. A group is labelled young if less than 30 per cent of its final mass is formed by $z \approx 1$.

In Figure 3 we present the luminosity gap $\Delta \mathrm{m}_{12}$ (within $0.5\mathrm{R}_{200}$) as a function of the brightest group galaxy magnitude in r-band, $M_r(BGG)$, given for all 39,132 groups (*i.e.*, groups with $M(R_{200}) \geq 10^{13}\ \mathrm{h}^{-1}\mathrm{M}_\odot$ and exist within both $z = 0$ and $z = 1$) using Guo *et al.* [20] SAM at the present epoch$(z = 0)$. The groups are colour-coded according to their $\alpha_{0,1}$ parameters(defined as "age" of systems), where $\alpha_{0,1} = M_{z \approx 1}/M_{z = 0}$. The horizontal line subdivides groups into magnitude gap bins. Those with $\Delta \mathrm{m}_{12} \geq 2$ are conventional fossil groups. Groups with $\Delta \mathrm{m}_{12} \leq 0.5$ are labelled as control groups which known to be young galaxy groups [22,23]. Vertical lines bin the groups according to the luminosity of their brightest galaxy (BGG) in 4 magnitude bins from -20.5 to -24.5. We note that the systems with large magnitude gap and faint BGGs are modest galaxies with some dwarf satellites, similar to the Milky Way. As these systems do not present galaxy groups, satisfying fossil groups condition, we limit our analysis to BGGs which are at least as bright as $M_R < -21.5$, *i.e.*, giant galaxies. This diagram shows that the galaxy luminosity gap combined with the luminosity of the brightest group galaxy for all halo mass over $10^{13}\ M_\odot h^{-1}$ is success to identify old groups with a probability of 61 per cent and young galaxy group with a probability of 92 per cent.

In order to achieve a higher success rate in identifying the old and young galaxy groups we use two other age indicators, the halo concentration and the off-set between the BGG and the halo luminosity/mass centroid (Figure 4). High mass concentration of fossil halos and the central position of the BGGs in fossil groups are the two build in property of X-ray selected fossil groups. Thus our new multi parameter space identification of the old galaxy systems resembles the properties of conventional fossils [2]. As a result, attention has to be paid when selecting fossil groups in the absence of X-ray data.

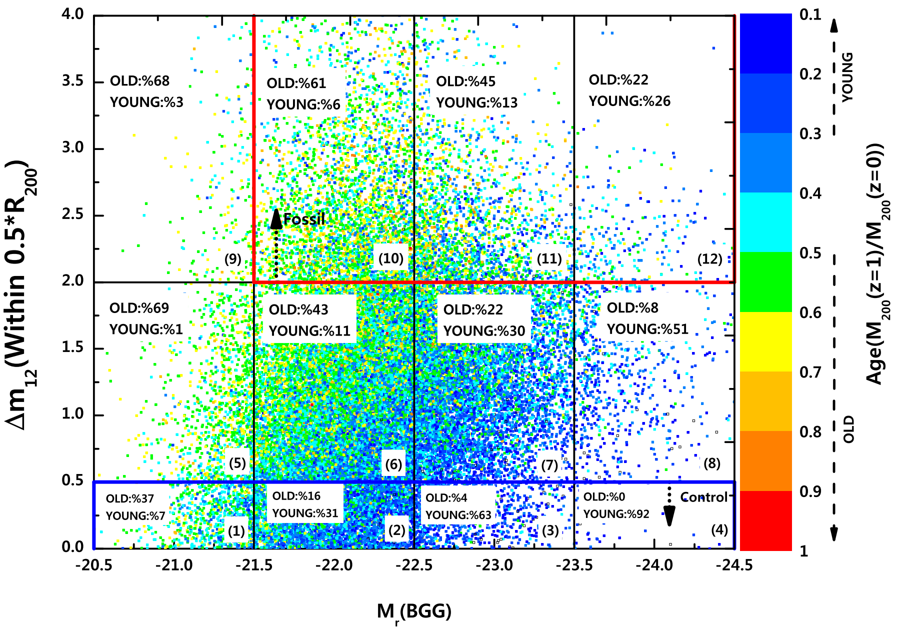

Figure 3. Distribution of the galaxy groups in the plane of luminosity gap Δm_{12} within $0.5R_{200}$ and the r-band magnitude of the Brightest Group Galaxy, $M_r(BGG)$, in the Millennium simulations with Guo *et al.* [20] semi-analytic model. Data point are colour-coded according to the ratio of the group halo mass at redshift $z \approx 1$ to its mass at $z = 0$ ($\alpha_{0,1}$). The red box defines fossil groups region, e.g., groups dominated by a giant galaxy and $\Delta m_{12} \geq 2$, while the blue box defines control groups with $\Delta m_{12} \leq 0.5$). The plane has been sub-divided into blocks within which the probability that the halo is old or young, is given. The plot has been adopted from Raouf *et al.* [3].

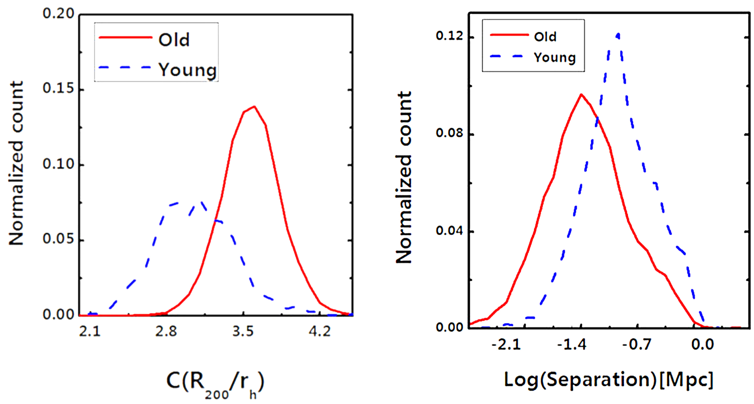

Figure 4. A comparison between the halo concentration (C) of old (red-line) and young (blue-dash-line) groups in MS using Guo *et al.* [20] **[left]**. The old systems show higher halo concentration than the young galaxy systems. The distribution of luminosity de-centring, the distance between the location of the BGG and the luminosity centroid **[right]**. Galaxy systems with a large luminosity de-centring are dynamically unrelaxed and thus younger. The plot has been adopted from Raouf *et al.* [3].

As mentioned above Gozaliasl *et al.* [11] offered a sample which allowed the semi-analytic models prediction of the luminosity gap statistics to be conducted at high redshift, similar to low redshift studies [24]. However, these models still lack the prediction of other observables such as the radio properties of galaxies. Our observations challenge these models both for their accuracy of the predictions.

4. Summary and Conclusions

Studies of fossil groups has evolved significantly over the past decade from the attempts to characterise the properties of individual or small sample to date in which they are employed to understand the formation and evolution of galaxy systems, IGM heating, AGN feedback and evaluating the galaxy formation models. In summary, observations and simulations suggest that fossil group halos are more concentrated in comparison to the general population of galaxy groups. The structural properties of their dominant galaxies differ from what is generally known for giant elliptical galaxies. Their IGM properties and the AGN activities of their brightest group galaxies are different to the general population of groups with a similar halo or galaxy masses. The studies of fossil groups have allowed us to probe the galaxy formation models implemented in cosmological simulations. These simulations also helped us to understand the formation and survival of fossil groups through hierarchical structure growth.

Author Contributions: Authors contributed equally to the analysis and presentation of the results in this paper (X-ray studies by Habib G. Khosroshahi; Radio studies by Halime Miraghaei; Numerical studies Mojtaba Raouf). The corresponding author presented the paper at the EWASS 2015 and wrote up the paper. The revision and the write up of the final version was led by Halime Miraghaei.

Conflicts of Interest: The authors declare no conflict of interest.

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