A Statistical Study of the Luminosity Gap in Galaxy Groups

SAEED TAVASOLI
Department of Physics, Ferdowsi University of Mashhad, Mashhad, Iran and School of Astronomy and Astrophysics, Institute for Research in Fundamental Sciences (IPM), P.O. Box 19395-5531, Tehran, Iran; tavasoli@ipm.ir

HABIB G. KHOSROSHAHI
School of Astronomy and Astrophysics, Institute for Research in Fundamental Sciences (IPM), P.O. Box 19395-5531, Tehran, Iran

ALI KOOHPAEI
School of Astronomy and Astrophysics, Institute for Research in Fundamental Sciences (IPM), P.O. Box 19395-5531, Tehran, Iran and Faculty of Science, Khajeh Nasir Toosi University of Technology, Tehran, Iran

HADI RAHMANI
Inter-University Center for Astronomy and Astrophysics, Post-Bag 4, Ganeshkhind, Pune 411007, India

AND

JAMSHID GHANBARI
Department of Physics, Ferdowsi University of Mashhad, Mashhad, Iran

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ABSTRACT. The luminosity gap between the two brightest members of galaxy groups and clusters is thought to offer a strong test for the models of galaxy formation and evolution. This study focuses on the statistics of the luminosity gap in galaxy groups in particular fossil groups, e.g., large luminosity gaps, in an analogy with the same in a cosmological simulation. We use spectroscopic legacy data of the seventh data release (DR7) of SDSS, to extract a volume-limited sample of galaxy groups utilizing a modified friends-of-friends (MFOF) algorithm. Attention is paid to galaxy groups in which the brightest group galaxy (BGG) is more luminous than $M_r = -22$. An initial sample of 620 groups in which 109 optical fossil groups were identified, where the luminosity gap exceeds 2 mag. We compare the statistics of the luminosity gap in galaxy groups at low-mass range from the SDSS with the same in the Millennium simulations where galaxies are modeled semianalytically. We show that the BGGs residing in galaxy groups with large luminosity gaps, i.e., fossil groups, are brighter, on average, and live in lower-mass halos with respect to their counterparts in nonfossil systems. Although low-mass galaxy groups are thought to have recently formed, we show that in galaxy groups with 15 galaxies brighter than $M_r \leq -19.5$, evolutionary process are most likely to be responsible for the large luminosity gap. We also examine a new probe of finding fossil groups, $\Delta m_{14} \geq 2.5$, and find that the fossil groups selected according to the new probe are more abundant than those selected using the conventional probe, $\Delta m_{12} \geq 2$, in a low halo mass regime, $\leq 10^{14} M_\odot$. In addition, we extend the recently introduced observational probe based on the luminosity gap, the butterfly diagram, to galaxy groups, and we study the probe as a function of halo mass. This probe can, in conjunction with the luminosity function, help to fine-tune the semianalytical models of galaxies employed in the cosmological simulations.

Online material: color figures

1. INTRODUCTION

Galaxy groups are key systems in advancing our understanding of structure formation and evolution in the universe, as they span the regime between individual galaxies and massive clusters in a hierarchical framework. Advances in the cold dark-matter cosmological simulations and improvements on the particle mass resolution have provided the opportunity to study galaxy groups or low-mass halos. The Millennium simulation (Springel et al. 2005) is a recent example. The semianalytical models of galaxy
formation are also employed to understand the formation and evolution of galaxies in a cosmological context.

The key factor in the success of this attempt is the availability of observational constraints to help fine-tune the models. While galaxy luminosity function has been widely used as a strong constraint, the number of physical processes and the free parameters in the models limit the achievements.

There is a class of galaxy groups, dubbed as fossil groups (Ponman et al. 1994), which are the archetypal relaxed systems and arguably the end product of the galaxy mergers within the group. The selection criteria for fossils are outlined by Jones et al. (2003), i.e., groups with an X-ray luminosity of $L_{\text{x, bol}} \geq 0.25 \times 10^{42} \text{ ergs}^{-1}$ and a minimum luminosity difference of 2 mag between the first- and second-ranked galaxies ($\Delta M_{\text{12}} \geq 2$), within half the projected $R_{\text{200}}$ radius, where $R_{\text{200}}$ is the radius within which the mean density is 200 times the critical density of the universe.

Implementation of cosmological simulations in which the evolution of the halos can be traced has given strong evidence that fossil groups, or galaxy systems with a large luminosity gap $\Delta M_{\text{12}}$, form earlier, on average, than galaxy groups with a small luminosity gap (Dariush et al. 2007, 2010). The early-evolution epoch for fossil groups had been argued previously based on observations of about a dozen such systems. They included the study of X-ray scaling relations (Khosroshahi et al. 2007) and the morphological studies of the brightest group galaxies (BGGs) in fossil groups (Khosroshahi et al. 2006).

A statistical comparison between the properties of observed fossil groups and those in the cosmological simulations requires dozens of such systems to be identified observationally, which is currently unavailable due to the nature of existing X-ray surveys (often shallow or very limited in angular coverage). Santos et al. (2007) cross-correlated optical and the Sloan Digital Sky Survey (SDSS) and the Röntgensatellit (ROSAT) All Sky Survey (Voges et al. 1999) and identified 34 fossil-group candidates covering a wide range of redshifts. However, the applied methodology does not produce a complete sample of fossil groups.

Although an X-ray threshold has conventionally been applied to the intergalactic medium (IGM) in fossil groups, much can be learned from the selection based on optical criteria alone: e.g., optical fossils (Dariush et al. 2007). Identifying low-mass fossil systems is hampered by the fact that groups are underrepresented in existing X-ray catalogs; however, based on simulation data, Dariush et al. (2007) have shown that even with applying X-ray criteria, the fraction of late-formed systems that are spuriously identified as fossils is $\sim 4$–$8\%$ of halo mass.

The main goal of this study is to learn the extent to which the luminosity gap in low-mass groups can shed light on the formation of these systems and to quantify the observed properties related to the luminosity gap, which can be compared with semianalytical models. As the large luminosity gap between the galaxies in a galaxy group can have a statistical origin, it would therefore be useful to learn to what extent the large luminosity gap is a representative of the evolutionary processes, as opposed to having been originated statistically. Furthermore, we provide observational measures that can be used to constrain the semianalytical models of galaxy formation.

This article is organized as follows: § 2 describes the databases and the simulations. The algorithm used to extract the sample of groups in observation is described in § 3. Biases and completeness of the sample are discussed in § 4. In § 5 we present the derived group properties. Selection criteria for identifying fossil groups are discussed in § 6. Results are presented and discussed in §§ 7–9, with concluding remarks presented in § 10.

For this study we assume that $h = 0.7$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

2. Data

2.1. Observation

We use the legacy archive of the latest data release of the SDSS, DR7 (Abazajian et al. 2009), which covers $8423 \text{ deg}^2$ in imaging data (which contains roughly 360 million distinct photometric objects), and the spectroscopic survey mapped $8032 \text{ deg}^2$ (1,640,000 objects with measured spectra). We confine the study to those objects identified in SDSS as galaxies. In this study, we use both the photometric and the spectroscopic data.

Initially, we restrict the study to galaxies within the redshift range of $0.02 < z < 0.17$, retaining only those with clean spectra (flag = 0), providing us with a sample of 601,981 galaxies. The lower limit on the redshift is dictated by the fact that objects with $z < 0.02$ are often stars, and the upper limit on redshift is placed in order to confine the study to the range where the spectroscopic sample is complete. It is worth stressing that the main galaxy spectroscopic sample of SDSS is restricted to Petrosian magnitude: $r_{\text{petro}} < 17.77$.

We extract objects with $r_{\text{petro}} < 21.0$, identified as galaxies, from the photometric sample of SDSS DR7. For galaxies fainter than $r_{\text{petro}} = 21.0$, the error in apparent magnitude increases rapidly (Oyaizu et al. 2008). For objects satisfying the preceding conditions, we retrieved the Petrosian magnitudes (Petrosian 1976; Strauss et al. 2002) and $K$-corrected them using the method described in Blanton et al. (2003a).

2.2. Simulation

In this article we use the galaxy group catalog from the Millennium simulation (Springel et al. 2005) and the associated semianalytical model of galaxy formation by Bower et al. (2006). Next, we briefly describe these simulations.

The Millennium simulation utilizes a ΛCDM cosmological model to follow structure formation from $z = 127$ up to the present epoch. Starting with an inflationary dark-matter-dominated universe, structures form through the bottom-up hierarchy: i.e.,
starting with small-scale density fluctuations resulting in large-scale structures we observe today. Evolution of $2160^3$ particles, each with $8.6 \times 10^8 \, h^{-1} \, M_\odot$, has been followed from $z = 127$ up to the present (64 time slices of positions and velocities were stored, separated logarithmically between $z = 127$ and $z = 0$) through a co-moving box of 500 Mpc on each side (Springel et al. 2005), with $\Omega_\Lambda = 0.75$, $\Omega_M = 0.25$, $\Omega_b = 0.045$, $h = 0.73$, $n = 1$, and $\sigma_8 = 0.9$ based on WMAP observations (Spergel et al. 2003) and the 2dF galaxy redshift survey (Colless et al. 2001). The evolution of a structure has been followed only if it is composed of at least 20 particles (equivalent mass is $1.72 \times 10^{10} \, h^{-1} \, M_\odot$) at that epoch (Springel et al. 2005). In addition, the friends-of-friends (FOF) algorithm was exploited to extract halos with densities of at least 200 times the critical density, and substructures were identified using the SubFind algorithm developed by Springel et al. (2001).

The underlying dark-matter halos of the Millennium simulation were used to simulate the growth of galaxies by self-consistently implementing a semianalytical model of galaxies on the outputs of the Millennium simulation (Bower et al. 2006). This semianalytical model accounts for the feedback from supernova explosions and active galactic nuclei (AGNs) in modeling the massive halos. In addition, AGN feedback has been considered as an operation that quenches the star formation, and star bursts are triggered both by merging and disk instabilities. Bower et al. (2006) predicted the luminosity function of galaxies in the $B$ and $K$ bands for the present epoch and the present-day color distribution. For the purpose of this study, we used the catalog of the Bower et al. (2006) semianalytical model and retrieved the absolute $r$-band magnitude for group members, the halo mass of the group, and the mass of the subhalo containing the BGG at the present epoch.

2.3. Monte Carlo Simulation

The idea behind performing the Monte Carlo simulation is that the luminosity gap between the two brightest members (or between any other members) of a galaxy system can also have a statistical origin.

We expect large luminosity gaps to appear preferentially in groups with few members. In order to understand the extent to which the luminosity gap with statistical origin affects our analysis and results, we perform a Monte Carlo simulation by drawing random samples from an underlying Schechter function (Schechter 1976).

We generate a sample of $\sim 10^6$ galaxy groups with different numbers of members within the completeness of the observed sample described in § 4. We choose the underlying luminosity function to have Schechter parameters of $\alpha = -1.08$ and $M_r^* = -21.62$ as in Zandivarez et al. (2006), with galaxy luminosity ranging from $M_r = -16$ to $-26$. The chosen values are the best-fit luminosity function for groups based on the $r$-band SDSS data.

3. SELECTING GROUPS IN OBSERVATIONAL DATA

3.1. The Algorithm

To identify galaxy groups, we use the modified friends-of-friends (MFOF) algorithm developed by Paredes et al. (1995), which is a modification of FOF (Huchra & Geller 1982), one of the most frequently applied methods for finding structures in redshift surveys. The starting point in this algorithm is that every galaxy can be the center of a group of galaxies; however, the algorithm will gradually lead to the most probable center for a given search radius.

Given this, we start by looking for companions of each galaxy within a specified search physical radius, $r_s$. A galaxy is a companion to the chosen galaxy if it falls within the search radius in the plane of the sky and within the redshift interval of $\Delta z$. For this study we choose $r_s$ to be the equivalent of 500 kpc at the redshift of the galaxy in the spectroscopic sample and $\Delta z = 0.002$.

For the first generation of the groups, we count the number of companions with the preceding constraints for each galaxy in the spectroscopic sample described in § 2.1. Naturally, most of the members will be shared by galaxy groups found in the first generation. Comparing overlapping groups, those with fewer members will be removed from the list if they fall within the $r_s$ measured from the center of the richer group and $\Delta z = 0.002$. This results in the second generation of the galaxy groups. Having this, we calculate the mean redshift and luminosity weighted center of each of the surviving groups and the process of removing the small groups overlapping with larger groups continues until there are no common members between any two groups of galaxies.

As was described, MFOF works with two free parameters, $r_s$ and $\Delta z$, and their values are set depending on the science goals of the study; e.g., Miller et al. (2005) and von der Linden et al. (2007) used $r_s = 1$ Mpc with $\Delta z = 0.002$ and $r_s = 2$ Mpc with $\Delta z = 0.01$, respectively, to identify cluster of galaxies. Also, Einasto et al. (2005) adopted $r_s = 0.5$ Mpc and $\Delta z = 0.002$ to make a catalog of groups/clusters. Here, we aim at studying galaxy groups and low-mass halos for which we find our choice suitable in comparison with the existing galaxy group catalogs. We extracted 81,614 and 6956 groups with more than two and five spectroscopic members ($\textit{richnesses}$), respectively.

There exist several catalogs of groups and clusters of galaxies extracted from the SDSS data: catalogs by Goto (2005, DR2), Miller et al. (2005, DR2), Merchant & Zandivarez (2005, DR3), Berlind et al. (2006, DR3), Zandivarez et al. (2006, DR4), Yoon et al. (2008, DR5), and Tago et al. (2008, DR5). In each of the previously mentioned catalogs, criteria implemented through the group-finder algorithm have been chosen on the basis of the type of the corresponding study. To check if our extracted groups, based on conditions adopted here, overlap with those from previous studies, we performed a cross-matching between our extracted catalog and two other popular group samples in the...
literature: the Abell cluster (Abell 1958) and C4 (Miller et al. 2005) catalogs. It worth stressing that although C4 is known as a galaxy cluster catalog, it has a wide mass range, making it suitable for the comparison with our galaxy group catalog.

For the redshift of Abell clusters we used published data by Struble et al. (1987), in which there are 838 with determined redshifts out of 2712 Abell clusters. There are 318 Abell clusters that lie in the area of sky coverage for the SDSS DR7 and have redshifts in the range of $0.02 < z < 0.17$. For our groups of richness $\geq 5$ (spectroscopic members), 195 out of 318 Abell clusters (61%) are matched within 10′ of our group center. In addition, we selected the groups of richness $\geq 2$ and, in this case, 283 out of 318 Abell clusters are matched (88%). The C4 catalog was generated using a cluster-finding algorithm, which identifies clusters as over dense regions in a seven-dimensional space of position and colors (Miller et al. 2005). The catalog contains 748 clusters, each with at least 10 members brighter than $r = 17.7$. Applying the preceding search criteria, we found 549 of 748 C4 clusters, with 73% within $0.02 < z < 0.17$. Reducing the number of galaxies per group to $\geq 2$, we would find 96% of C4 clusters, which shows a very large overlap between our extracted groups and the C4 catalog.

3.2. Color-Magnitude Relation

As noted earlier, the main spectroscopic sample of the SDSS is complete to the Petrosian $r < 17.77$. However, the photometric sample reaches lower luminosities. Moreover, the tiling algorithm used in the SDSS spectroscopic survey (Blanton et al. 2003b) leaves some galaxies unobserved spectroscopically, because of fiber collisions. Yoon et al. (2008) estimated the spectroscopic completeness of the SDSS DR5 to be $f_{\text{spec}} \sim 65\%$ for rich clusters. In order to have a realistic estimate of the optical luminosity and the richness of the extracted groups, we use the color-magnitude relation (CMR) to identify additional group-member candidates. Observational evidence has shown that the bulk of the early-type galaxies in clusters and groups lie along a linear CMR. This relation is shown to have a small scatter (e.g., Bower et al. 1992; Peebles et al. 2002; Kodama et al. 1998) and can be used as a robust method for finding galaxy systems (e.g., Gladders et al. 2000). Although there are uncertainties in the CMR method of group-membership identification, we use the photometric members only to estimate the global properties, such as the number of galaxies per groups and the total luminosity of the group.

In order to incorporate the photometric data into the analysis, we consider all the photometric and spectroscopic galaxies within an angular distance equivalent to 500 kpc around the group center if they fall on the CMR. It should be noted that group center is defined as the brightest member of the group. For this purpose, we fit a line to the color-magnitude diagram of the spectroscopic members if the group has at least three members with $M_r \leq -19.0$. We determine the slope and intercept of the CMR for each group. We consider only those photometric ($m_r \leq 21$) and spectroscopic galaxies that fall within $\pm 2\sigma$ of the color-magnitude relation defined by spectroscopic members. An example of a fitted CMR to color-magnitude diagram for one of our groups is shown in Figure 1.

Member selection using the color-magnitude relation method is hampered by misidentification of foreground and background galaxies as group members. In principle, misidentification of members will affect the total luminosity and, in turn, the estimated mass (§ 5.2). In order to quantify the uncertainty in halo mass estimate, we randomly selected field regions in the SDSS. We chose galaxies within a radius comparable with that of groups in each field region and applied color-magnitude selection. The contribution of the field galaxies on the halo mass of groups was found to be negligible.

We assume all the photometric group members found using the CMR to have the mean redshift of the group defined by the spectroscopic members.

4. Bias Correction and Completeness

As noted in § 2.1, we have used the main spectroscopic sample and photometric legacy survey of SDSS DR7 as our spectroscopic and photometric input. Statistical properties of the input data are discussed here, along with the constraints that resulted from the completeness and bias removal from the samples. For the photometric sample, Abazajian et al. (2009) demonstrated that the sample is 95% (95% completeness limit for point sources) complete to $r \approx 22.2$. Whereas the main spectroscopic sample of SDSS DR7 is complete to a $r$-band Petrosian magnitude (Petrosian 1976) of $r \approx 17.77$, corrected for Galactic extinction (Schlegel et al. 1998; Strauss et al. 2002; Abazajian et al. 2009).

![Figure 1](https://example.com/figure1.png)

**Fig. 1**—Color-magnitude relation for members residing within a centered at the BGG position with a radius of 0.5 Mpc at the BGG redshift. The $2\sigma$ boarders and restrictions on apparent magnitude are also illustrated. See the online edition of the PASP for a color version of this figure.
The limiting magnitude of $r \approx 17.77$ is equal to $M_r \approx -17$ at $z = 0.02$ and $M_r \approx -21.8$ at $z = 0.17$. As we are interested in large luminosity gaps, i.e., $\Delta m_{12} \geq 2$ mag, the preceding completeness limit will naturally bias our analysis toward low-luminosity gaps at the higher end of the redshift distribution. This is shown in Figure 2.

To overcome this, we apply the $M_r \leq -22$ constraint to the BGGs, both in the observed SDSS groups (4113 groups) and in the simulations (18843 groups). The constraint on the BGG luminosity is also consistent with the value adapted for the $M^*$ parameter in Schechter luminosity function in the $r$ band. In addition, this selection helps to compensate the absence of X-ray data, given the correlation of the BGG luminosity with the IGM X-ray emission (Khosroshahi et al. 2007; Ellis & O'Sullivan 2006), and thus reduces contamination from individual galaxies that are not associated with a group-scale halo.

To ensure that a luminosity gap up to 2.5 mag can be observed without a bias, the second-brightest galaxy should be at least as luminous as $-19.5$ mag, which corresponds to the limiting apparent magnitude of the spectroscopic sample; i.e., $r \approx 17.77$ mag at $z = 0.065$. In other words, our luminosity-gap estimates of less than 2.5 mag should be bias-free for groups within $0.02 \leq z \leq 0.065$. We therefore restrict the observed galaxy sample to the preceding redshift range.

Applying the previously mentioned restrictions ($\Delta m_{12} \leq 2.5$ and $z \leq 0.065$) resulted in 109 fossils out of 620 groups (see § 6).

5. ESTIMATING PHYSICAL PARAMETERS FOR GROUPS

Based on available parameters for members of each galaxy group, we have derived a number of quantities for both simulated and observed groups, which are discussed here.

![Diagram of 4113 groups with $M_{r,BGG} \leq -22$ in redshift vs. $\Delta m_{12}$. The rectangle area represents the selected region that is free of biases. See the online edition of the PASP for a color version of this figure.](image)

5.1. Velocity Dispersion and Virial Radius

According to Beers et al. (1990), a reliable method for measuring the velocity dispersion in groups with few members is the so-called gapper estimator (e.g., Yang et al. 2005). Since our group’s catalog contains low member groups, we use this method to estimate the line-of-sight velocity dispersion of each individual group.

The method involves ordering the set of recession velocities $v_i$ of the $N$ group members and defining gaps as

$$g_i = v_{i+1} - v_i, \quad i = 1, 2, \ldots, N - 1.$$  

(1)

The rest-frame velocity dispersion of our groups is then given by

$$\sigma_{\text{gap}} = \sqrt{\frac{\pi}{(1 + z_{\text{group}})N(N - 1)}} \sum_{i=1}^{N-1} w_i g_i,$$  

(2)

where the weight is defined as $w_i = i(N - i)$. As the central galaxy in each group is assumed to be at rest with respect to the dark-matter halo, the estimated velocity dispersion has to be corrected by a factor of $\sqrt{N/(N - 1)}$ (Yang et al. 2005). This results in a final velocity dispersion given by

$$\sigma_v = \sqrt{\frac{N}{N - 1} \sigma_{\text{gap}}}.$$  

(3)

As we will see in the next section, an estimation of the virial radius of the galaxy groups is also required. Using the virial theorem, Girardi et al. (1998) derived an approximation for the virial radius of a spherical system as

$$R_{\text{vir}} = \frac{\sqrt{3} \sigma_v}{10 H_0} \text{ Mpc},$$  

(4)

where $\sigma_v$ is the velocity dispersion of group members.

On the other hand, for the simulated groups, given that the halo mass is derived directly by adding the mass of the dark-matter particles, $R_{\text{vir}}$ is calculated as follows:

$$R_{\text{vir}} = \frac{GM_{\text{halo}}}{\sigma_v^2} \text{ Mpc},$$  

(5)

where $M_{\text{halo}}$ is the total mass of the halo and $\sigma_v$ denotes the velocity dispersion of group members.

5.2. Halo Mass

For observed groups, the total luminosity was used as a diagnostic of halo mass, as it appeared to be a better mass estimator than the line-of-sight velocity dispersion (Popesso et al. 2005; Miller et al. 2005; Lin et al. 2004):
\[ \log(h^{-1}M) \approx -2.46 + 1.45 \log(h^{-2}L_r), \]  

(6)

where \( L_r \) is the total \( r \)-band luminosity of the galaxy group, defined as the sum of the \( r \)-band luminosity of member galaxies with \( M_r < -19.5 \) (Milosavljevic et al. 2006).

In addition to the measurement of \( M_{\text{halo}} \) in the simulated groups, we also estimate the halo mass using the empirical relation (eq. [6]), for consistency. In Figure 3, the two methods of mass estimation are compared. The left panel compares the distribution of the halos in the plane of total gravitational mass based on equation (6) and the luminosity of the BGG for both the simulated and the observed systems. The same is shown in the right panel, with the mass of the simulated halos obtained from the dark matter only. As expected, a better consistency is achieved when the luminosity-based estimation is applied to the observations and the simulations. Therefore, this mass indicator is used in the our analysis to avoid any systematics. The same method was applied in assigning a mass to the halos in the Monte Carlo simulations (see § 2.3).

5.3. Richness

To obtain the number of galaxies per group, we applied \( M_r \leq -19.5 \) criterion to the observed and the simulated groups (Millennium and Monte Carlo). The distribution of richness for the observed and the simulated groups is shown in Figure 4. This plot illustrates that the richnesses of simulated and observed groups are different, which might be related to different group selection procedures in simulation and observation data. The group selection in simulations is based on a full knowledge of the three-dimensional distribution of dark-matter subhalos (e.g., galaxies), whereas, as noted earlier, the group selection in observations is based on two-dimensional distribution of galaxies, complemented by slices the redshift space. However, the difference in shape of the distributions has no impact on our conclusions.

In order to study the impact of biases on statistics of number of galaxies per group, generated groups through the Monte Carlo simulation had to span a large range of richnesses (\( 10^4 \) simulations were carried out for each richness class of the group).

6. SELECTION OF FOSSIL GROUPS

In low-density environments, the merging of compact groups can lead to the formation of the fossil groups (Vikhlinin et al. 1999; Jones et al. 2003). These classes of systems have masses that are comparable with those of normal groups and clusters of galaxies. Observationally, the identification of fossils so far has been based on the definition of fossil group suggested by Jones et al. (2003). In the Jones et al. (2003) definition, a fossil group has an X-ray luminosity of \( L_{\text{X,bol}} \geq 0.25 \times 10^{42} h^{-2} \text{ergs}^{-1} \), and the dominant galaxy is at least 2 mag brighter (in the \( r \) band) than the second-ranked galaxy within \( 0.5 R_{200} \) of the group.

Assuming a circular orbit, the \( L^* \) galaxies merge with the central galaxy within a few billion years, due to orbital decay as a result of the dynamical friction (Jones et al. 2003).

The existing X-ray surveys overlapping the area covered by the SDSS survey are either wide and shallow (ROSAT All Sky Survey; Voges et al. 1999) or very small and deep. As a result, facing the lack of suitable X-ray data, we limit the study to optical fossils or galaxy groups with a large luminosity gap (Dariush et al. 2007). The X-ray criteria are conventionally used to ensure that only group-mass halos have been selected. As
noted earlier, we compensate for this by the introduction of a lower limit in the BGG luminosity.

The luminosity gap was measured within half of a virial radius, $R_{\text{vir}}$, derived using equations 4 and 5. This is slightly different from the definition of Jones et al. (2003); however, the difference consistently applies to both the simulations and observations.

Similar to observational constraints discussed in § 4, the same conditions was applied to simulation data to select optical fossil groups, with the exception of the X-ray luminosity criterion. Also following Dariush et al. (2007), we limit the analysis to groups with $\log(M_{\text{halo}}/h^{-1} M_\odot) > 13$.

These conditions resulted in 1993 fossil systems out of 16,688 groups, or roughly 12%. Furthermore, fossil groups through the Monte Carlo simulation were defined as groups $\Delta m_{12} \geq 2$ and $M_{r,\text{BGG}} \leq -22$, in accordance with definitions for observation and simulation data.

In order to compare the properties of fossil with nonfossil groups, we introduced control groups with $\Delta m_{12} \leq 0.5$ and that satisfy the remaining conditions mentioned previously (e.g., $M_{r,\text{BGG}} \leq -22$) in observations and simulations. This provides us with 85 and 2419 control groups in observed and simulated catalogs, respectively.

7. FOSSIL GROUPS: BGG LUMINOSITY AND HALO PROPERTIES

As noted earlier, fossil groups are distinguished by a large gap in the luminosity of the two brightest members, indicating the absence of $L^*$ galaxies. If the BGGs in fossil groups are the product of the mergers of $L^*$ galaxies, then they are expected to be statistically brighter than the BGGs in nonfossil groups.

Figure 5 shows the distribution of the $r$-band absolute magnitude, $M_r$, for fossil and control BGGs. As expected, the fossil BGGs are brighter than control BGGs in both the simulated and observed groups. This is also shown in a study by Diaz-Gimenez et al. (2008), where they used simulations to demonstrate that the fossil BGGs accrete larger stellar mass, on average, as a result of earlier formation of the epoch and larger frequency of mergers.

In Figure 6, we compare fossil and control groups in the plane of group mass and the BGG luminosity. It illustrates that for a given $r$-band luminosity of the BGG, control-group halos are statistically more massive than fossil-group halos.

8. LUMINOSITY GAP STATISTICS

As noted in § 2.3, for some of the properties studied in this article, there exists a probability that random processes contribute in part to the observed trends. In the following, we will specifically study the contribution of random processes on halo properties of groups.
independent of the luminosity of the brightest galaxy in both the observed and simulated galaxy systems. However, the same increases with the luminosity of the brightest member in Monte Carlo-generated groups. The shape of the luminosity function is what drives the trend seen in the Monte Carlo-generated systems. The probability of finding low-luminosity galaxies is larger in comparison with luminous galaxies in the Schechter function; thus, for a fixed \( M^* \), more luminous BGGs would result in a statistically larger luminosity gap. The fact that such a trend is not pronounced in the observed sample and in the cosmological simulation supports the argument that the large luminosity gap is unlikely to have a statistical origin. Moreover, as shown in Figure 7a, the fraction of fossil groups in the observations and the simulation are larger than the same predicted by the Monte Carlo simulations.

Figure 7b shows the same as a function of group richness. As expected, the probability of finding a large luminosity gap (\( \Delta m_{12} \geq 2 \)) decreases with increasing richness. However, the trend is the fastest for the Monte Carlo-generated groups, whereas observed groups show a weaker dependency on richness.

In the regime of low richness, the probability distributions of the observed, simulated, and randomly generated groups coincide. As a result, it appears that the luminosity gap in such systems is driven by random processes; i.e., evolutionary mechanisms have played a negligible role in forming the luminosity gap. This is statistically supported by the hierarchical structure formation paradigm in which the low-mass halos (poor galaxy groups) are recently formed. Dariush et al. (2007) concluded the same based on a comparison of simulated (Millennium) and Monte Carlo-generated groups. This study extends their findings to the observed groups.

On the other hand, in richer groups, the Monte Carlo prediction of the large-luminosity-gap incidence is significantly lower than those in cosmological simulations and in the observations suggesting that the luminosity gap in richer systems is predominantly driven by evolutionary processes. Moreover, it is noticeable that the cosmological simulation based on the semianalytical model of Bower et al. (2006) predicts a lower probability for fossil groups, in the entire richness range, than the same in the observed sample. Furthermore, the choice of group-finding algorithms in observations and simulations could also contribute to this difference. The probability distribution therefore helps to probe the accuracy of the semianalytical models.

In Figure 7c we show the fraction of fossil groups in each mass bin. For Monte Carlo-generated groups, it is prominent that the fraction of fossil groups in each mass bin decreases as the halo mass increases. As noted earlier, masses of each Monte Carlo-generated group were assigned according to the total-luminosity method. Therefore, we expect that both the richness of the groups and the luminosity of bright members determine the halo mass. For fossil groups (and generally for systems with a large luminosity gap), the BGG luminosity is

![Figure 7](https://example.com/figure7.png)

**Figure 7:** Top: Percentage of fossil groups in each absolute magnitude bin for randomly generated, observed, and simulated groups. Middle: Percentage of fossil groups in each richness bin. Bottom: Fossil percentage in each halo mass bin for simulated, observed, and randomly generated groups. In richer and more massive groups the evolutionary processes dominate the random processes. See the online edition of the *PASP* for a color version of this figure.
a more defining factor, because of the presence of the large luminosity gap. Thus, fossil fraction in each mass bin is strongly linked to the BGG luminosity and the richness of the group.

Comparing the probability distributions of observed, simulated, and randomly generated groups illustrates that the three distributions coincide in the low-mass end. Consequently, low-mass fossil groups are predominantly statistical; i.e., evolutionary processes are not playing a significant role in forming the luminosity gap in these systems. On the contrary, at the high-mass end, a fraction of the fossils are substantially higher than those predicted by the Monte Carlo simulation, both in the cosmological simulations and in the observations, indicating the role of evolutionary mechanisms in forming $\Delta m_{12}$. Interestingly, the semianalytical model adopted for this study predicts a lower fraction for fossil groups across most of the mass/richness range. It is hard to point out at a single physical process employed in the simulations to interpret the offset between the fossil fraction in the observations and simulations, as this could be a consequence of various assumptions in handling of non-gravitational processes such as the star-formation efficiency, AGN feedback, and cooling. These could be coupled with gravitational processes such as the merger rate.

We propose the luminosity gap to be an observational constraint for the semianalytical models in addition to the luminosity function and the color of galaxies.

8.2. Luminosity-Gap Probability Distribution

We study the probability distribution of a luminosity gap. The distributions are shown for two richness regimes, richness $\leq 5$ and richness $\geq 15$, in Figure 8. It is noticeable that although the probability distributions in observed and simulated groups follow a similar trend: they deviate from Monte Carlo predictions at $\Delta m_{12} \geq 1.2$ and $\Delta m_{12} \geq 0.75$ for low and high richnesses, respectively, such that the fraction of observed and simulated groups with a given $\Delta m_{12}$ are larger than randomly generated groups.

We interpret this as an impact of evolution: assuming that the primordial distribution of $\Delta m_{12}$ was predicted by Monte Carlo simulation, the evolutionary mechanisms always work in the direction of increasing the luminosity gap.

Von Benda-Beckmann et al. (2008) suggested an inverse process: transforming systems with large luminosity gaps to those with low $\Delta m_{12}$. In this scenario, there is always a probability that new galaxies fall into groups and hence disrupt the luminosity gap. For instance, they have shown that the luminosity gap is strongly affected by galaxy infall and hence is a transient characteristic of galactic systems. Other processes may also affect the luminosity gap, including mergers between galaxy groups. However, when two galaxy systems merge, they end up in considerably more massive systems and hence with higher richness than the progenitors. This also works in the direction of decreasing the luminosity gap.

![Normalized histogram of $\Delta m_{12}$ for two separate richness regimes](image)

Figure 8.—Normalized histogram of $\Delta m_{12}$ for two separate richness regimes (see § 8.2).

9. NEW CRITERION FOR FINDING FOSSIL GROUP; $\Delta m_{14}$

In a recent study based on the Millennium simulation by Dariush et al. (2010), a new indicator based on gap magnitude between the first- and fourth-brightest galaxies within half of the virial radius of the group $\Delta m_{14} \geq 2.5$ is presented to be a more efficient probe of identifying early-formed halos than the conventional definition of a fossil galaxy group: i.e., $\Delta m_{12} \geq 2$.

Dariush et al. (2010) found that the mass assembly histories of the halos identified by the two methods are similar, on average. About 90% of fossil groups that were identified according to $\Delta m_{12}$ and $\Delta m_{14}$ criteria in earlier epochs become nonfossils after $\sim 4$ Gyr, and the fossil phase itself lasts $\sim 1$ Gyr. The main difference between the two methods seems to be in the efficiency of finding early-formed halos (Dariush et al. 2010).

In order to evaluate the abundance of fossil groups according to these definitions, we compared the luminosity-gap distribution based on simulation and observation data (our catalog).

To be able to estimate the luminosity-gap parameter $\Delta m_{14}$, groups with the following properties are selected. The extracted groups have at least four members within the half of the virial radius of the galaxy group, and the brightest and fourth-brightest galaxies should be at least as luminous as $-22$ and $-19$, respectively. Applying the preceding criteria, 163 groups were
identified in our catalog, out of which 41 groups meet the $\Delta m_{14} \geq 2.5$ criterion.

Among these observed fossil groups ($\Delta m_{14} \geq 2.5$), 12% satisfy the conventional definition of fossil ($\Delta m_{12} \geq 2$). Conversely, 56% of $\Delta m_{12} \geq 2$ satisfy the $\Delta m_{14} \geq 2.5$ criterion. Hence, a large proportion of the population of groups identified with the $\Delta m_{14} \geq 2.5$ criterion are not in common with those identified by the $\Delta m_{12} \geq 2$ criterion. This is consistent with the findings of Dariush et al. (2010) based on simulations.

We applied the same criteria to extract galaxy group in simulation data. Out of 16,688 groups, 1993 and 2973 groups satisfy the $\Delta m_{12} \geq 2$ and $\Delta m_{14} \geq 2.5$ criteria, respectively.

In Figure 9, we plot the $R$-band luminosity-gap distribution $\Delta m_{12}$ and $\Delta m_{14}$ from our observations and simulations. Results show that the luminosity gap from simulation is in fair agreement with observations, and both present similar distributions for the $\Delta m_{12}$ and $\Delta m_{14}$ luminosity gap. The fraction of groups with $\Delta m_{12} \geq 2$ in observation and simulation are 17% and 12%, respectively, and these values for the $\Delta m_{14} \geq 2.5$ indicator are 25% and 18%, respectively.

The probability of finding fossil systems according to these definitions in the current analysis is different from the statistics reported by Dariush et al. (2010), who used the group catalog of Yang et al. (2007) based on SDSS DR4. For instance, Dariush et al. (2010) reported 2.0% and 2.1% in observation and simulation, respectively, when using $\Delta m_{12} \geq 2$. For $\Delta m_{14} \geq 2.5$, they found 6.2% and 5.1%, respectively. The difference is due to the completeness considerations in sample selection adapted by us.

The most important difference between our group catalog and that of Yang et al. (2007) is the additional constraint we have imposed on BGG luminosity and the luminosity gap (see § 4). Furthermore, their groups are defined as systems that have at least four members, whereas we require the group to have two spectroscopic members within half of the virial radius.

In § 8.1, it was found that the probability of finding early-formed system, i.e., fossil groups $\Delta m_{12} \geq 2$, is higher in low-mass systems. In Figure 10, the abundance of fossil groups based on conventional definition $\Delta m_{12} \geq 2$ and the new indicator $\Delta m_{14} \geq 2.5$ are given as functions of halo mass. This shows that in comparison with conventional fossils ($\Delta m_{12} \geq 2$), the fossil groups based on $\Delta m_{14} \geq 2.5$ are more abundant in the low-mass range $\log(M/h^2 M_{\odot}) < 14.3$. Above this mass limit, the statistics are poor and therefore hard to interpret.
Fig. 11.—Top: Distribution of $r$-band absolute magnitude for the first-brightest (open circles) and second-brightest (filled circles) group members as a function of $\Delta m_{12}$ for different halo masses. Bottom: Evolution of slopes and intercepts of brightest group member as a function of halo mass. See the online edition of the PASP for a color version of this figure.
10. DISCUSSION AND CONCLUSION

In this study we extend the earlier observational studies of luminosity gap to low-mass regime and provide observational constraints for semianalytical models based on this observation. We extract 620 groups in SDSS DR7 utilizing the MFOF algorithm and measure the luminosity gap between the two brightest galaxies in the group, \( \Delta m_{12} \). This results in 109 groups with \( \Delta m_{12} \geq 2 \), within half a virial radius, known as optical fossil groups. In addition, the Bower et al. (2006) semianalytical model employed on the Millennium simulation was used to select 16,688 groups with 1993 fossil groups in the same manner as that applied to the observational data. A Monte Carlo simulation was also performed to generate a large sample of luminosity-gap statistics purely drawn at random from the Schechter luminosity function to investigate the importance of the random processes.

We show that fossil BGGs in both observations and simulations are, on average, brighter than those in control galaxy groups. Given a relatively poor constraint on galaxy velocity dispersion in groups (e.g., dynamical mass estimation), we adapted the total-luminosity method for the estimation of the total gravitational mass of the groups based on empirical relations. We show that fossil-group halos are found to be statistically less massive than those of the control sample for a given BGG luminosity.

We confirm that the luminosity gap in systems with low richness is predominantly driven by random processes, whereas evolutionary mechanisms are responsible for large luminosity gap in rich groups.

We find indications that the fraction of fossil groups based on the \( \Delta m_{12} \geq 2.5 \) criterion is higher than that when adopting the conventional \( \Delta m_{12} \geq 2 \) criterion. This is valid mostly to the low-mass end.

Following a recent study by Smith et al. (2010) based on a sample of massive galaxy clusters (\( \sim 10^{15} M_\odot \)), we propose a test based on the luminosity gap in the galaxy group, the butterfly diagram \( M_r \) vs. \( \Delta m_{12} \), which is found to be able to discriminate between different galaxy-formation models in groups and clusters when a large sample of groups with known luminosity gap is available. Extending their study to low-mass groups, we compare 620 observed groups and 16,688 simulated groups in the plane of \( M_r \) vs. \( \Delta m_{12} \) (Fig. 11). The absolute magnitudes of the brightest and second-brightest galaxies within the group are plotted as functions of \( \Delta m_{12} \) for different halo masses. Linear regressions are also presented for both the brightest and the second-brightest galaxies as functions of \( \Delta m_{12} \). In addition, Figure 11 shows the variation of the slope and the intercept of the linear fit as functions of the halo mass for BGGs.

We find that the slope of the BGG brightness in the Bower et al. (2006) simulation is steeper than the observed BGGs, particularly in the high-mass regime. This implies that the AGN feedback in BGG is too weak in the Bower et al. (2006) semianalytical model (Smith et al. 2010). Further improvements have been made recently in the semianalytical model (Bower et al. 2008), driven by constraints from the IGM properties of the galaxy systems, which also required a retuning of the galaxy-formation parameters in their earlier model to be able to reconstruct the galaxy luminosity function in the local universe.

The discussion on the success of their changes in the context of the luminosity gap requires a direct comparison of the two semianalytical models (Bower et al. 2006, 2008). We find that the BGG brightness of observed groups increases with halo mass. In contrast, this trend is not clear in simulated groups. Furthermore, in the high-mass bin, the absolute magnitude of the simulated BGG span is \( \sim 2.5 \) mag, in contrast to the observed range of \( \sim 1 \) mag. Smith et al. (2010) argued that the large spread in the absolute magnitude of simulated BGGs is driven by the higher efficiency of the conversion of the cold gas into stars. We note that in low-mass bin, where the random processes are dominated, the spread in the luminosity of the observed and simulated BGGs are nearly the same (\( \sim 0.5 \) mag).

The correlation between the slope of the line fitted to BGG in Figure 11 and halo mass points to an increasing contribution of the evolutionary mechanisms in forming the luminosity gap in more massive halos. Giving the considerable space density of large-luminosity-gap groups (e.g., Vikhlinin et al. 1999; Jones et al. 2003; van den Bosch 2007; D’Onghia et al. 2005; von Benda-Beckmann et al. 2008; Dariush et al. 2007), it seems that the butterfly diagram is a simple way of testing the accuracy of the semianalytical models.

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