Evolution of Compact and Fossil Groups of Galaxies from Semi-analytical Models of Galaxy Formation

Amin Farhang1, Habib G. Khosroshahi1,2, Gary A. Mamon2, Ali. A. Dariush3, and Mojtaba Raouf1

1 School of Astronomy, Institute for Research in Fundamental Sciences (IPM), P.O. Box 19395-5746, Tehran, Iran; a.farhang@ipm.ir
2 Institut d’Astrophysique de Paris (UMR 7095: CNRS & UPMC, Sorbonne-Universités), 98 bis Bd Arago, F-75014 Paris, France
3 Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

Received 2016 December 25; revised 2017 March 27; accepted 2017 March 30; published 2017 May 4

Abstract

We compare the mean mass assembly histories of compact and fossil galaxy groups in the Millennium Dark Matter Simulation and an associated semi-analytic galaxy formation model. Tracing the halo mass of compact groups (CGs) from \(z = 0\) to \(z = 1\) shows that, on average, 55\% of the halo mass in CGs is assembled since \(z \sim 1\), compared to 40\% of the halo mass in fossil groups (FGs) on the same time interval, indicating that compared to FGs, CGs are relatively younger galaxy systems. At \(z = 0\), for a given halo mass, FGs tend to have a larger concentration than CGs. Investigating the evolution of CG’s parameters reveals that they become more compact with time. CGs at \(z = 0.5\) see their magnitude gaps increase exponentially, but it takes \(\sim 10\) Gyr for them to reach a magnitude gap of 2 mag. The slow growth of the magnitude gap leads to only a minority (\(\sim 41\%)\) of CGs selected at \(z = 0.5\) turning into a FG by \(z = 0\). Also, while three-quarters of FGs go through a compact phase, most fail to meet the CG isolation criterion, leaving only \(\sim 30\%)\) of FGs fully satisfying the CG selection criteria. Therefore, there is no strong link of CGs turning into FGs or FGs originating from CGs. The relation between CGs and FGs is thus more complex, and in most cases, FGs and CGs follow different evolutionary tracks.

Key words: cosmology: theory – cosmology: dark matter – galaxies: evolution – galaxies: groups – Galaxy: halo – methods: numerical

1. Introduction

Compact groups of galaxies (CGs) are small galaxy systems in which at least four luminous galaxies are found to be in a compact configuration, with a typical intergalactic separation of the order of the scale of the constituent galaxies. Although the first CG was found by Stephan (1877), it was only after the first large survey, i.e., the Palomar Observatory Sky Survey (POSS), that the number of CGs increased substantially. In the mean time, CGs were also cataloged in the Atlas of Interacting Galaxies (Vorontsov-Velyaminov 1959, 1977) and the Atlas of Peculiar Galaxies (Arp 1966). These catalogs contain information on galaxies or galaxy groups selected on the basis of observed signatures of interaction or peculiar appearance. Later studies by Hickson et al. (1977) and Heiligman & Turner (1980) identified CGs based on specific, quantitative criteria from analysis of their morphological features in the POSS photographic imaging plates. These efforts led to the publication of the first catalogs of CGs, e.g., the Rose catalog (Rose 1977) and the Hickson CG catalog (HCG; Hickson 1982). More catalogs of CGs were then compiled by applying Hickson’s criteria to large-sky surveys such as the Sloan Digital Sky Survey (SDSS, Lee et al. 2004; McConnell et al. 2009) and the Two Micron All-Sky Survey (Díaz-Giménez et al. 2012).

Studies of CGs indicate that these groups have star formation rates, colors, and morphological types that put them somewhere between binary and isolated galaxies (Mamon 1986; Moles et al. 1994; Tovmassian et al. 2006). Based on observations, the median projected galaxy separation in Hickson CGs is approximately \(\sim 39\ h^{-1}\) kpc with a line-of-sight velocity dispersion of \(\sim 200\) km s\(^{-1}\) (Hickson et al. 1992). In such an environment, the dynamical timescale is very short, which in turn makes it commonplace for galaxy–galaxy mergers and interactions. Thus, galaxies in CGs tend to be different from the field population, so the fraction of early-type galaxies in CGs, in magnitude-limited surveys, is significantly higher than that in the field. For instance, Hickson & Rood (1988) found that \(\sim 51\%)\) of galaxies in their sample of CGs are early-types, compared to \(\sim 20\%)\) in the field (Gisler 1980). Also, Carnevali et al. (1981), Barnes (1985), and Mamon (1987) studied short dynamical and galaxy merging times within dense groups. As early-type galaxies can be formed via the mergers of late-type systems (e.g., Barnes 1990), these observations can be explained by frequent interactions and mergers among galaxies in the environments of CGs (Mamon 1986, 1987).

Torres-Flores et al. (2013) found that the Tully–Fish jump is similar to those found for field galaxies. Coenda et al. (2012) found that the galaxies in CGs are more concentrated, have higher surface brightness, and are smaller in size than galaxies in the field and loose groups. Similarly, Martínez et al. (2013) found that brightest group galaxies (BGGs) in CGs are more concentrated and have a larger surface brightness than their counterparts in both high-mass and low-mass loose groups. Sohn et al. (2013) studied the activity in galactic nuclei in CGs and found a strong (respectively weak) environmental dependency of AGN fractions for early-type (late-type) galaxies in CGs. Coenda et al. also found that, while the luminosity function of galaxies in CGs has a characteristic magnitude comparable to that of the most massive loose groups, its faint-end slope is similar to that of loose groups of intermediate stellar mass. Moreover, these authors have shown that the environment of CGs contains more early-type and red galaxies compared to field and loose groups. Finally, the X-ray observations of ROSAT, ASCA, Chandra, and XMM-Newton have led to the detection of hot, X-ray-emitting gas from many CGs (Ponman et al. 1996; Mulchaey & Zabludoff 1999; Desjardins et al. 2013; Fuse & Broming 2013).
In a compact galaxy system, luminous (hence massive) galaxies are close to one another in projection and are expected to rapidly merge together (Carnevali et al. 1981; Schneider & Gunn 1982; Barnes 1985; Mamon 1987). Several scenarios have been proposed to explain the survival of CGs against the rapid merging of their galaxies: (i) the appearance of the compact configuration is caused by a chance alignment along the line of sight of galaxies belonging to a parent group (Rose 1977; Walke & Mamon 1989) or cosmological filament (Hernquist et al. 1995); (ii) CGs may be transient unbound cores of loose groups (Rose 1977); and (iii) CGs of galaxies continually form within a single rich collapsing group, where the dwindling galaxy membership caused by mergers is replenished by new incoming galaxies (Diaferio et al. 1994). Analytical estimates suggest that the replenishment by infall is sufficient (Mamon 2000). The closest known CG in the Virgo cluster (Mamon 1989) is almost certainly a product of a chance alignment of galaxies, given the redshift-independent distances to its members (Mamon 2008). Analyses of semi-analytical models of galaxy formation indicate that roughly two-thirds of CGs selected with HCG criteria are physically dense, while the remaining one-third are caused by chance alignments of galaxies, mostly within virialized groups (Díaz-Giménez & Mamon 2010, see also McConnachie et al. 2008).

If galaxies in CGs are physically close, then galaxies should rapidly merge and form a very luminous, e.g., giant elliptical galaxy (Carnevali et al. 1981; Schneider & Gunn 1982; Mamon 1986, 1987; Barnes 1989; Dubinski 1998). One may then conclude that CGs are the progenitors of the so-called fossil groups (FGs; Ponman et al. 1994), which are dominated by an isolated giant elliptical galaxy surrounded by X-ray-emitting diffuse hot gas (Barnes 1992; Jones et al. 2003). Unfortunately, it is difficult to observationally distinguish between a real 3D dense environment of CGs and chance alignments within loose groups, because of the redshift-space distortion uncertainties (Walke & Mamon 1989). On the other hand, cosmological N-body simulations provide a 3D view of groups and thus allow the study of the nature and properties of CGs (McConnachie et al. 2008; Díaz-Giménez & Mamon 2010) and their evolution in time.

In this paper, we select compact and FGs purely on the basis of their halo properties from the Millennium Dark Matter Simulations, as well as galaxy properties associated with dark matter halos as characterized by semi-analytic models (SAMs). We trace back in time both FGs and CGs, up to $z=1$. Our aims are to (a) investigate the evolution of the CGs in comparison with fossil galaxy groups and (b) address the question of whether there is an evolutionary connection between the two types of galaxy groups, i.e., fossils and compacts, and more specifically if CGs evolve into FGs.

In Section 2, we present the various simulation suites used in this work. In Section 3, we describe the procedure followed to select compact, fossil, and control groups using SAM catalogs of galaxy formation. We then describe how mock data have been constructed from a SAM catalog. Our final results are described in Section 4.

2. Data

Over the last decade, the Cold Dark Matter (CDM) model, complemented by the dark energy field $\Lambda$, has been the concordance model for structure formation in the universe. While the initial growth of density perturbations is linear, the subsequent hierarchical build-up of structures is a highly nonlinear process that is only accessible through numerical simulations (e.g., Springel et al. 2005). Since the mass component of CDM, which interacts gravitationally, is represented by point particles, the $N$-body simulations can be used to simulate initial perturbations as well as the collapse and formation of structures.

In this study, we use the Millennium Dark Matter Simulation (Springel et al. 2005) along with the publicly available SAM of De Lucia & Blaizot (2007). While the former provides us with the halo properties of galaxy groups, the latter helps to characterize the physical properties of group’s constituent galaxies.

2.1. The Millennium Simulation

The Millennium Simulation, which is based on the $\Lambda$CDM model, consists of a comoving periodic box (sides $500 h^{-1}$ Mpc) of $2160^3$ particles of individual mass $8.6 \times 10^8 h^{-1} M_\odot$, and a gravitational softening length of $5 h^{-1}$ kpc (Springel et al. 2005). The simulation covers a redshift range from $z=127$ to the present day and is based on an inflationary universe, leading to a bottom-up hierarchy of structure formation, which involves the collapse and merger of small/dense halos at high redshifts into modern-day observed large virialized systems such as groups and clusters. The cosmological parameters adopted by the Millennium Simulation are $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $\Omega_b = 0.045$, $n = 1$, and $\sigma_8 = 0.9$, with the Hubble parameter $h = 0.73$. The locations and velocities of all dark matter particles in the simulation are saved in 64 timesteps roughly logarithmically spread between $z=127$ and $z=0$.

In the Millennium Simulation, dark matter halos are identified down to a resolution limit of 20 particles, yielding a minimum halo mass of $1.72 \times 10^{10} h^{-1} M_\odot$. Halos in the simulation were found using a Friends-of-Friends (FoF) group finder algorithm, leading to the identification of halos with overdensities of at least 200 times the critical density. Sub-halos are subsequently extracted from the FoF halo with the SUBFIND algorithm (Springel et al. 2001). Therefore, for any given halo, a merger tree can be built by output tables at individual epochs. This enables us to hierarchically trace through time the growth of halos and their associated sub-halos within the dark matter simulation.

2.2. Semi-analytic Models

The physical processes in galaxies (e.g., the star formation, thermal evolution of the interstellar medium, the growth of supermassive black holes) occur on very small scales, whereas the evolution of structures happens on cosmological scales. Hence, it is very time-consuming to follow the details of the physical processes in a single hydrodynamical simulation.

A useful alternative is to rely on SAMs of galaxy formation and evolution (Kauffmann et al. 1993; Cole et al. 1994), which evolve galaxies as single entities applying physical recipes to evolve them. SAMs have played an important role in improving our understanding and interpretation of physical processes taking place in galaxies during their evolutions. De Lucia & Blaizot (2007) have designed an SAM and run it on the halo merger trees of the Millennium Simulation. These merger trees contain sub-halos, and galaxy mergers occur when sub-halos merge into their parent halos or with one another.
The resulting catalog (the delucia2006a table in the Millennium database) contains 9 million galaxies at \( z = 0 \), down to a limiting absolute magnitude of \( M_R - 5 \log h = -15.5 \), observed in the \( B, V, R, I \), and \( K \) filters. There are some differences between the SAM of De Lucia & Blaizot and other SAMs such as Bower et al. (2006), Font et al. (2008), and the most recent model of Henriques et al. (2015). However, for the purpose of our study, which focuses on the evolution of the halos, and given the relative success in previous studies (e.g., Gozaliasl et al. 2014), we adopt the SAM developed by De Lucia & Blaizot (2007) for our current investigation.

3. Construction of Simulated Group Samples

3.1. Database

We select all halos, identified by the FoF method, from the dark matter halo catalog of the GAVO database\(^4\) at \( z = 0 \) with halo mass \( M(R_{200}) \geq 10^{13} h^{-1} M_\odot \). Group galaxy members associated with these halos were selected from the De Lucia & Blaizot (2007) SAM output (delucia2006a table) of GAVO. The halo-mass threshold was applied to ensure that the progenitors of the present-day galaxy groups are indeed groups at \( z \sim 1.0 \) with at least four galaxy members (Darwish et al. 2010). The evolution of each group was then followed, from \( z = 0 \) to \( z = 1.0 \), in 23 discrete snapshots equally spaced in \( \log z \), by matching haloIDs to their progenitors at earlier epochs. In addition, the BGG position of each galaxy group, as well as the position of its host dark matter halo, were used to identify group members by using fofID and haloID keys in the SAM catalog. This helps to retrieve optical properties of group member galaxies from the semi-analytic galaxy catalog at any redshift.

3.2. Mock Redshift-space Catalog

A mock redshift-space catalog can be constructed from the real-space SAM using the algorithm described in Blaizot et al. (2005), but without the box transformations (translation, rotation and flipping) or replication. To do so we have performed the following steps.

1. We place the observer at one of the vertices of the simulation box and use the line of sight to the observer as the timeline of the light cone.
2. We convert the Cartesian coordinate system to celestial coordinates (i.e., R.A., and decl.).
3. We compute the redshift of each galaxy following Duarte & Mamon (2015). To perform this, we solve \( d_{\text{comov}}(z_{\text{com}}) = \sqrt{X^2 + Y^2 + Z^2} \) for the cosmological redshift \( z_{\text{com}} \). And then we obtain the galaxy redshift by applying the Doppler shift at the cosmological redshift by \( 1 + z = \sqrt{(1 + \beta)/(1 - \beta)(1 + z_{\text{com}})} \), where \( \beta \) is the line-of-sight component of the peculiar velocity divided by the velocity of light: \( \beta = v_p/c = d/d \).
4. The luminosity distance \( D_L \), and therefore the magnitude of each galaxy, are then computed.
5. Finally, k-corrections are applied to correct the apparent magnitudes, using the color-based method of Chilingarian et al. (2010).

\(^4\) http://gavo.mpa-garching.mpg.de/Millennium/

3.3. Samples of Simulated Groups

We select samples of mock FGs and CGs from the Millennium Simulation. In addition, following the previous studies of FGs (e.g., Darwish et al. 2007, 2010), we also select a mock control sample whose properties are similar to normal galaxy groups (Smith et al. 2010), without being fossil or compact. We choose to work with redshift-space samples, since CGs can only be selected in redshift-space.

3.3.1. Fossil Groups

Using the conventions introduced by Jones et al. (2003), FGs are systems that have the following properties:

- **Dominant galaxy**: the difference in magnitudes between the two BGGs within \( 0.5 \, R_{200} \) should have \( \Delta m_{12} = r_2 - r_1 \geq 2 \). Here, \( R_{200} \) is the radius of the sphere centered on the halo in which the critical density is 200 times the mean density of the universe.

According to the scaling relation between halo mass and X-ray luminosity, an X-ray luminosity of \( L_{X, \text{bol}} \geq 10^{42} h^{-2} \text{ erg s}^{-1} \) in the Millennium simulation corresponds to a halo mass of \( M_{200} \geq 10^{13} h^{-1} M_\odot \) (Darwish et al. 2007, 2010). Hence, halos of our selected FGs meet a minimum mass limit (see Section 3.1). In Section 4.1, the other samples of FGs will be described in more detail.

We compile two samples of FGs. In the first one, FGs are selected based on the DeLucia2006a (De Lucia & Blaizot 2007) real-space catalog in the Millennium 3D volume and in the second one, fossils are identified in the mock catalog (redshift-space).

Some real-space FGs may no longer be classified as fossils in redshift-space due to the projection effects. In other words, the FG criterion \( (\Delta m_{12} \geq 2 \) within \( 0.5 \, R_{200} \)) is a more conservative constraint in redshift-space than in real-space. To explore this, we trace back the halo-mass evolution of what we call *hybrid* FGs, i.e., the real-space FGs that fail to be identified as redshift-space FGs, against those identified as fossils in the mock catalog (i.e., redshift sample).

3.3.2. Compact Groups

CGs are selected from the mock catalog, using an automated search algorithm similar to the one described by Hickson (1982). In doing so, the following criteria were applied to the FoF galaxy groups.

- **Population**: \( N \geq 4 \) galaxies within 3 mag from the brightest (\( m_b \)) in the \( R \) band.
- **Compactness**: mean surface brightness \( \mu_R \leq 26 \) mag arcsec\(^{-2} \), within the smallest circumscribed circle of angular diameter \( \theta_c \) containing the galaxy centers;
- **Isolation**: distance to nearest neighboring galaxy in the same magnitude range building a larger circle of angular diameter \( \theta_N \geq 3 \theta_c \). In other words, the concentric annulus of angular radii between \( \theta_c \) and \( 3 \theta_c \) must be devoid of galaxies in the \( [m_b, m_b+3] \) magnitude range, and is called the isolation annulus.

In Figure 1, the surface brightness \( \mu \) and the angular diameter of the ratio of the largest to the smallest concentric circles \( \theta_N/\theta_c \) are compared to those estimated by Mendel et al.
The Astrophysical Journal, 840:58 (10pp), 2017 May 1

4. Results

4.1. Mass Assembly History of Fossil Groups

In previous studies of the evolution of FGs from galaxy formation simulations, FGs were selected in real-space (Dariush et al. 2007, 2010). But since our aim is to investigate the connection between CGs and FGs by studying their mass assembly histories (MAHs) in the Millennium Simulation, and since CGs are selected in redshift-space, we first identify fossils in redshift-space and then verify whether their geometric mean MAH is consistent with earlier results based on the 3D approach.

We measure the errors $\epsilon$ on the mean MAH, $\langle M(z)/M(z=0) \rangle$, by considering the square root of the sum of the squared statistical errors, with the cosmic variance. The statistical error on the mean is $\sigma_{\text{stat}} = \sqrt{1/N}$, where $\sigma$ is the standard deviation of the MAH for the groups of the considered type at the considered redshift and $N$ is the number of these groups at that redshift. We measure the cosmic variance by dividing the simulation box into 8 cubic sub-boxes of half the box size, and writing that the cosmic variance is 1/8th of the variance $\sigma_{\text{sub-boxes}}^2$ of the means of the 8 boxes. The errors $\epsilon$ on the mean MAH then satisfy

$$\epsilon^2 = \sigma_{\text{stat}}^2 + \frac{\sigma_{\text{CV}}^2}{N} + \frac{\sigma_{\text{sub-boxes}}^2}{8}. \quad (1)$$

At low masses, the cosmic variance is of the same order as the statistical uncertainties, but at high masses, statistical uncertainties are dominant. The same error estimation was done for all group samples.

Figure 2 compares the mean MAHs, $M/M_{z=0}$ of the different FG samples. One clearly sees that while real-space and redshift-space FGs have the same mean MAH, suggesting a high degree of similarity between the mean MAHs in both samples.

4.2. Mass Assembly History of Compact Groups

The MAH of each group was then traced from $z = 0$ to $z = 1$ in 23 discrete snapshots, equally spaced in log $z$. We then considered the mean MAH, $\langle M/M_{z=0} \rangle$, averaging over all $z = 0$ groups for all CG, FG, and control group samples.

Figure 3 compares the mean MAHs of fossil, compact, and control groups from $z = 0$ to $z = 1.0$. From this figure, it is clear that, in agreement with previous studies (e.g., Dariush et al. 2007), FGs have assembled a larger fraction of their halo mass at earlier epochs in comparison to control groups. The mean MAH in CGs falls in between those of fossil and control groups. At low redshifts $z \lesssim 0.2$, the mean MAH of

(2011), from a compilation of CGs, based on the SDSS DR6 data. As is clear in Figure 1, there is a fair agreement between the observed and simulated distributions of the group surface brightnesses on one hand and of the distance to the closest neighbor in units of group sizes on the other hand, although the simulated CGs are more likely to be very compact ($\mu < 24$ mag arcsec$^{-2}$) and very isolated ($\theta_{\text{sf}}/\theta_{\text{fg}} > 5$) than the ones that were extracted by Mendel et al.

3.3.3. Control Sample

A sample of control groups has also been selected as a representative of predominantly young galaxy groups. Control groups are systems with $\Delta m_{12} \leq 0.5$ within $0.5 R_{200}$. In addition, they do not belong to either FGs or CGs.

Table 1, summarizes the number of groups of different types in the Millennium mock catalog (and in the Millennium 3D catalog for the case of the real-space sample). The number of real-space FGs is 15% higher than the corresponding number of redshift-space FGs. Also, 82% of real-space FGs (8296) are also in the redshift-space FG sample, which means that 18% of real-space FGs (1854) do not meet the fossil criteria in redshift-space.

### Table 1

Mock Group Samples

| Group Sample                        | Number |
|------------------------------------|--------|
| All (non-compact, real-space)      | 51538  |
| Fossil (real-space sample)         | 10150  |
| Fossil (redshift-space sample)     | 8751   |
| Fossil (hybrid: in real-space but not in redshift-space) | 1854   |
| Control                            | 10625  |
| Compact                            | 2330   |

**Note.** All groups are extracted from the $z = 0$ (De Lucia & Blaizot 2007) semi-analytic model output and have a halo mass $M(R_{200}) \geq 10^{13} h^{-1} M_{\odot}$.
compact groups is very similar to that of FGs and of control groups, with a surprisingly slightly faster recent growth of FGs relative to CGs and control groups for $z \lesssim 0.1$, i.e., 1.5 Gyr.

To better understand the observed discrepancy in the mean MAH of compact and control groups, given the differences in their selection criteria, we select two more samples of control groups by applying the same magnitude gap criterion, but instead of considering the first- and second-ranked galaxies to be within $R_{\text{vir}}/2$, we select them to be within $R_{\text{vir}}/4$ and $R_{\text{vir}}/6$ and trace back their most massive progenitors. As Figure 4 shows, decreasing the radius within which the first two BGGs is selected from $R_{\text{vir}}/2$ to $R_{\text{vir}}/6$ (logically the next step after $R_{\text{vir}}/4$ should be $R_{\text{vir}}/8$, but there are too few group members at this radius, hence we test $R_{\text{vir}}/6$ instead) causes the mean MAH in control groups to approach the one seen in CGs at $z \lesssim 0.5$. This suggests that, in comparison to control groups, the observed trend in CGs is dictated by its compact configuration. However, the distribution of the angular sizes of the CGs (angular radii, $\theta_G$, of the smallest circumscribed circle), shown in Figure 5, covers a wide range of values, including those estimated within $R_{\text{vir}}/2$ in FGs, as well as the ones derived for control groups within $R_{\text{vir}}/2$, $R_{\text{vir}}/4$. Hence, CGs seem to behave heterogeneously compared to the fossil and control samples.

To explore whether the results depend upon the $z = 0$ halo mass, we have repeated the above procedure in three different bins of final halo mass. Figure 6 shows that while the mean MAHs of fossil, compact, and control groups each depend on final halo mass (except, surprisingly, the FGs between the intermediate-mass and high-mass bins), the hierarchy of mean MAHs between fossil, compact, and control groups remains the same as in Figures 3 and 4: at $0.3 < z < 1$, the most massive progenitors of the $z = 0$ control groups grow faster than those of the CGs, which in turn grow faster than those of the FGs; but at $z < 0.1$, the mean growths of the most massive progenitors are very similar between the three classes of groups, with the most massive progenitors of $z = 0$ FGs showing a slightly
more rapid growth than the corresponding progenitors of compact and control groups.

4.3. Concentration

Large magnitude gaps in galaxy groups are generally believed to be caused by galaxy mergers, as the most massive (luminous) galaxies grow through mergers, usually by merging with the second-ranked galaxy (Mamon 1987). The (group) halo concentration can change the rate at which galaxy mergers occur in a galaxy group: according to the Chandrasekhar (1943) formula, the rate of mergers by dynamical friction roughly scales as 
\[ r_{\text{circ}}^3, \]
which for Navarro et al. (1996; NFW) models at fixed virial quantities leads to a slightly lower rate of mergers for higher concentrations at a given ratio of radius over virial radius, as shown in Figure 7. In high-concentration NFW halos, the higher densities are offset by even higher third powers of the circular velocities.

It is well known that, for a given final halo mass, higher-concentration halos assembled earlier (Wechsler et al. 2002). Therefore, if FGs assemble earlier than CGs, we expect their \( z = 0 \) concentrations to be higher than those of CGs.

We describe the dark matter with an NFW density profile:
\[
\rho_{\text{NFW}} = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2},
\]
where \( r_s \) is the scale radius (where the logarithmic slope of the density profile is equal to -2), while \( \rho_s = 4\rho(1) \) is a characteristic density. The “standard” concentration of the halo can be defined as \( c = c_{200} = r_{200}/r_s \), where \( r_{200} \) is the enclosing mean density of 200 times the critical density. At \( z = 0 \), relaxed halos in ΛCDM cosmological simulations have median concentrations decreasing, with slope \( \approx -0.1 \), from 6.5 to 5 for \( \log(hM_{200}/M_\odot) \), increasing from 13 to 14.5 (e.g., Navarro et al. 1997; Neto et al. 2007; Prada et al. 2012). Unrelaxed halos have concentrations roughly one-third lower (Neto et al. 2007). Finally, the distribution of concentrations of relaxed halos of a given halo mass is roughly lognormal, with a dispersion of 0.1 dex (Neto et al. 2007).

Unfortunately, the scale radius \( r_s \) is not readily available in the Millennium database. Instead, the concentration could be defined on the ratio of the virial radius to the radius containing half the mass enclosed within the virial sphere: \( c_h = r_{200}/r_h \). But this definition of concentration does not capture the standard concentration, since for NFW models, \( c_h \approx 1.45^{c/0.28} \) for reasonable values of \( c \), i.e., \( c_h \) ranges in the small interval from 2.0 to 2.6 for \( c \) varying from 3 to 8.

We therefore followed Prada et al. (2012) in defining the concentration of galaxy groups from
\[
\frac{v_{\text{max}}}{v_{200}} = 0.465 \sqrt{1 + c/\ln(c + 1)},
\]
where \( v_{\text{max}} / v_{200} \) is a U-shaped function of \( c \) that reaches a minimum of unity at \( c = 2.163 \), which corresponds to the radius where the circular velocity curve is at maximum. Equation (3) can thus only be solved if \( v_{\text{max}} / v_{200} > 1 \), which ensures that the solution of Equation (3) for \( c \) has two roots. We thus solve Equation (3), adopting the greater of the two solutions for \( c \), i.e., the one with

Figure 6. Geometric mean MAHs of the most massive progenitors of compact (blue open circles), fossil (red filled circles), and control groups (green open diamonds) in three different bins of final halo mass, increasing from left to right.

Figure 7. Ratio of the merger rate \( \langle n_{\text{mer}}/v_c^3 \rangle \) to that of a \( c = 4 \) halo for NFW models, assuming circular orbits with the Chandrasekhar (1943) formula.
Since the maximum circular velocity is reached at a radius of 2.163 $r_h$ and since our virial radii satisfy $r_{\text{vir}} = c r_h \geq 2.163 r_h$, it is guaranteed that the radius of maximum circular velocity is smaller than the virial radius. Finally, we compute the virial velocity from $v_{\text{vir}} = \sqrt{G M_{200}/r_{200}}$, where $G = 43.01$ (km s$^{-1}$) Mpc$^{-1}$ $M_{\odot}$ is Newton’s gravitational constant.

In Figure 8, we compare the concentration–mass relations of fossil, compact, and control groups. At a given halo mass, the concentration parameters of CG halos tend to be 10% smaller than those of FGs, but 10% larger than those of control groups. In all three classes of galaxy groups, the correlation between the mass and concentration is well defined. A power law provides a good description of the median concentration as a function of halo mass, and we find:

$$c_{\text{FG}}^c = 12.16 \left( \frac{h M_{200}}{10^{13} M_{\odot}} \right)^{-0.08},$$

$$c_{\text{CG}}^c = 11.14 \left( \frac{h M_{200}}{10^{13} M_{\odot}} \right)^{-0.1},$$

$$c_{\text{control}}^c = 9.95 \left( \frac{h M_{200}}{10^{13} M_{\odot}} \right)^{-0.1}.$$  

4.4. Evolution of Parameters

We now analyze the time evolution of CG parameters, i.e., group mean surface brightness $\mu_R$, group outer isolation ring ($\theta_R$), and inner ($\theta_C$) angular radii (see Section 3.3.2), by tracing back the parameters of the present-day ($z=0$) CGs to the epoch when they are no longer compact. Since most CGs disappear within the first few snapshots before $z=0$, the sample size becomes too small for reasonable statistical measurements. For example, among 2330 CGs at $z=0$, only six groups remain compact at $z=0.3$. We therefore trace back the CG parameters only to $z=0.2$ where ~140 CGs remain.

Figure 9 shows that for $z=0.2$ to $z=0$, CGs evolve with slightly increasing surface brightness (a decrease of 0.1 in surface magnitude). This slightly higher surface brightness at

FIGURE 8. Halo concentration parameters $c = r_{200}/r_h$ (derived by solving Equation (3) for $c$) as a function of halo mass, for fossil, compact, and control groups at $z = 0$. The symbols represent the median concentration in bins of the same mass divided by the square root of the halo number in the bin masses.

lower than those of the FGs. In addition, as the middle panel of Figure 6 shows, the assembly times of CGs are similar to those of FGs in the mass bin $13.5 \leq \log (h M/M_\odot) < 14$ of the final halo mass, so the concentrations of CGs are closer to those of FGs at $\log (h M/M_\odot) < 13.5$ and 13.7 in Figure 8, which confirm the above picture.

In some X-ray or lensing surveys, massive clusters have unusually high concentrations. For instance, using X-ray data, Buote et al. (2007) found that $\log (h M/M_\odot) = 13.5$ groups have a dark matter concentration $c = 15$, defined using the virial radius, i.e., $c \approx 11$, when the outer radius is taken to be $r_{200} \approx r_{\text{vir}}/1.35$ for NFW models of reasonable concentration.

Using kinematical modeling, Mamon (2007) found that, dynamically hot ($\sigma_c > 300$ km s$^{-1}$) X-ray-selected groups have $c > 10$, while cold ($\sigma_c \leq 300$ km s$^{-1}$) groups mostly are located at $c < 5$, where the concentrations are measured for the total distribution of mass. Our high standard concentrations are thus consistent with dynamically hot X-ray-selected groups.

Is the existence of a gap in the galaxy luminosity function in “fossil” systems the “last state” or is it a “transitory phase” in the group evolution? Many works have attempted to address this issue. For instance, von Benda-Beckmann et al. (2008) showed that many groups will go through a “fossil phase,” which typically will end with new infalling satellites from the environment and cause the phase to cease. Furthermore, Cui et al. (2011) found no significant difference in the central galaxy properties in the FGs and non-FGs. These findings were consistent with the analysis carried out by Darush et al. (2010), who showed that regardless of the redshift at which FGs are identified, after ~4 Gyr, more than ~90% of them become non-FGs. Moreover, beyond the extent of 7.7 Gyr (time interval between $z = 0$–1) very few groups retain a 2 mag gap between their two brightest galaxies. This provides clear evidence that the FGs are simple groups that temporarily are in a “fossil phase.” On the other hand, in current work, we find that FGs have a higher concentration than the control groups, which may be due to the fact that in regular systems the concentration is higher than that in the merging systems, and FGs are known to have avoided recent mergers.

5 Almost all of the concentrations for galaxy/group-scale objects analyzed by Buote et al. (2007) were taken from the literature. These studies measured the concentrations by including separate components for the stellar mass and the dark matter. If the stellar mass component had been omitted, then the concentration parameters for those galaxy/group-scale systems would have been larger (Mamon & Lokas 2005), and presumably the slope of the c-M relation measured by Buote et al. (2007) would have been steeper in that case. For massive clusters, including the stellar mass of the BCG component typically has little effect on the concentration.
Evolution of galaxies within group radii simultaneously fade by decreasing by in CG angular radius would lead to the surface magnitude radius of the group \( z(z = 0) \) of luminous or smaller (or both) than their CG progenitors at \( z = 0.2 \). As shown in Figure 9, the projected radius of the CG (\( \theta_{\text{CG}} \)) is \( \sim 1.5 \) times larger at \( z = 0.2 \) than its radius at the current epoch (\( z = 0 \)). If the group luminosity were fixed, this decrease in CG angular radius would lead to the surface magnitude decreasing by \( -0.9 \), hence the group luminosity must simultaneously fade by \( \approx 0.8 \) mag. Also, the angular isolation radius of the group (\( \theta_{\text{CG}} \)) experiments a similar decrement over time. Therefore, the ratio of \( \theta_{\text{CG}}/\theta_{\text{CG}} \) remains almost unchanged (open stars).

According to Figure 9, the evolution of CGs since \( z = 0.175 \) occurs at nearly constant group stellar mass (it increases by only 0.6\%). This slow increase of stellar mass is consistent with the negligible growth of the total galaxy stellar mass (summed over all progenitors) found by De Lucia & Blaizot (2007) for brightest cluster galaxies (their Figure 7). During the same period, the CG total luminosities dim by 20\%, which is roughly as expected from passive evolution of a constant-mass stellar population. This luminosity dimming is too small to compete with the decrease of CG size by a factor 1.5, which is the main contributor to the increase of the mean surface brightness by a factor of 1.9.

Furthermore, we select CGs at \( z = 0.5 \) (selected in the same way as described in Section 4), trace their evolution forward to \( z = 0 \), and follow the evolution of the magnitude gap (selected within the half-virial radius). According to Figure 10, the fraction of groups with large (\( \Delta m_{\text{12}} > 2 \)) magnitude gaps increases with time from 5\% to 20\%, and thus some CGs turn into fossils by \( z = 0 \). But this process does not significantly contribute to the population of the present-day FGs, as the fossil phase does not survive for a long time and a galaxy group may go through the fossil phase several times during its evolution (e.g., Dariush et al. 2010).

4.5. Connection between Compact and Fossil Groups

We wonder if any connection exists between CGs and FGs. For instance, do all CGs evolve into FGs? In other words, are FGs the end products of galaxy mergers in CGs (Mamon 1987; Barnes 1992; Jones et al. 2003)? Also, do all FGs go through a compact phase before evolving into their form in the present epoch?

To address these questions, we study the progenitors of the present-day FGs to determine, statistically, what fraction of them went through a compact phase at earlier epochs. More precisely, FGs are initially identified in redshift-space in the mock catalog at \( z = 0 \), and at every previous snapshot we check whether any of their progenitors are compact (they may no longer be an FG) by applying the CG selection criteria at each redshift slice. We iterate this analysis up to \( z = 1 \), unless a progenitor of the \( z = 0 \) FG is found to meet the CG criteria at a given \( z < 1 \) snapshot. We find that only \( \approx 23\% \) of the present-day FGs were also CGs at some stage in the past (see Table 2). Note that the probability that a galaxy group satisfies both compact and fossil criteria simultaneously is only \( \lesssim 3\% \) in any snapshot within the redshift range \( 0 \lesssim z \lesssim 1 \). We also trace forward the CGs selected at \( z = 0.5 \) up to \( z = 0 \) and check whether any of these groups turn into FGs. We also proceed until a CG meets the FG criteria at a given \( 0.5 < z < 0 \) snapshot. We find that \( \approx 41\% \) of CGs become FGs during their evolution. Therefore, most CGs do not have enough time for their magnitude gap to grow above 2 mag. This can also be deduced from Figure 11, which indicates that it takes over 10 Gyr, since \( z = 0.5 \) for the mean gap of CGs, to grow above 2 mag.

The snapshots are spaced by 350 Myr at \( z = 1 \) and 260 Myr at \( z = 0 \). Could the CG phase be shorter than the time resolution of the Millennium Simulation? Using several tens of \( N \)-body simulations, Mamon (1987) concluded that dense
Table 2
Link between Compact and Fossil Groups

| Conversion                     | Observer       | Fraction      |
|--------------------------------|----------------|---------------|
| Simultaneous FG                | box center     | 0.03 ± 0.02   |
| Progenitor of FG was CG         | box center     | 0.23 ± 0.03   |
| Progenitor of FG was CG         | any            | 0.36 ± 0.02   |
| CG turns into FG                | box center     | 0.41 ± 0.03   |

Note. Row 1: probability of a galaxy group to simultaneously be a fossil (FG) and compact (CG) at 0 ≤ z ≤ 1; Row 2: probability that a progenitor of a z = 0 FG is a CG identified at 0 < z ≤ 1; Row 3: probability that the BGG of a z = 0 FG is the most luminous galaxy of a CG identified at 0 < z ≤ 1, for any observer in the simulation box; Row 4: probability that a CG at z = 0.5 turns into a FG by z = 0.

Figure 11. Evolution of the magnitude gap for various sets of compact groups: compact groups selected at z = 0.5 and traced forward to z = 0, where the gap is measured for the two most luminous galaxies within the virial radius (blue strip) or within half the virial radius (plum strip). Also shown are compact groups of eight galaxies run in the N-body simulations of virialized groups by Mamon (1987), with either individual dark matter halos (orange squares), or a common dark matter halo (green circles).

groups of galaxies lose their CG appearance in projection in typically 750 Myr if the dark matter is around the individual galaxies, and nearly 4 times longer if the dark matter is in a common envelope. Therefore, the CG phase lasts longer than the time between the Millennium snapshots, and we should hence have missed very few CGs.

Note that in the above exercise, the selection of groups in the redshift-space as described in Section 4 is based on an observer located at the center of the simulation box. Therefore, the BGG of a FG that is selected based on the “absolute” magnitude is not necessarily the brightest galaxy of a CG (which is selected based on the “apparent” magnitude) if applying the compact criteria. Thus, we can also move around the position of an observer in the simulation box such that a progenitor of the BGG of an FG is always the brightest galaxy in the CGs found among the progenitors of the FG (rather than considering a fixed observer’s position). In this case, we find that around ∼36% of z = 0 FGs were also CGs at epochs 0 < z ≤ 1.

If only a minority of FGs have gone through the CG phase, and if the large magnitude gaps in FGs are signs of more rapid mergers than those seen in control groups, one must conclude that such rapid merging can occur in groups that fail to meet the Hickson CG criteria. Since the galaxy merger rates are higher in dense systems (where the dynamical times are shorter), one suspects that the HCG compactness criterion is not the issue, but rather the HCG isolation criterion. In other words, the progenitors of FGs should have sufficiently dense cores for rapid merging to occur and thus for the magnitude gap to grow, but these cores are not necessarily isolated from their surroundings. To address this idea, we trace back the progenitors of FGs that have CG populations of at least 4 galaxies and go through a compact phase, but we do not consider the isolation criteria up to z = 1. We then find that ~72% of today’s FGs satisfy the HCG compactness and population, but fail to meet the isolation criteria.

Figure 11 shows the evolution of the magnitude gap, Δm12, for the 3123 CGs identified in the Millennium Simulation at z = 0.5 and in sets of 50 N-body simulations of virialized dense groups of 8 “halos” by Mamon (1987). In these simulations, each galaxy was represented by a single particle, with an additional particle for the intragroup background. Each particle had structure, mass, and energy, which were exchanged between particles during mergers, rapid collisions, and lost to the background (particle) through dynamical friction (which puffed up the background particle). As expected, Δm12 increases rapidly in time, and Mamon (1987) concluded that this rise in magnitude gap is the consequence of galaxy mergers. The linear trend of the semi-log plot of Figure 11 indicates an exponential increase of the magnitude gap in CGs. Figure 11 also shows that the magnitude gap grows a little faster after 2 Gyr when we select the two most luminous galaxies within half the virial radius (instead of within rvir). The slower growth of the gaps of CGs selected at z = 0.5 in the (cosmological) Millennium Simulation relative to that in the idealized simulations of virialized groups of Mamon (1987) probably arises from luminous infalling galaxies that fill the gap.

5. Conclusions

In this work, we extracted FGs and CGs from the outputs of the De Lucia & Blaizot (2007) semi-analytical model, run on the dark matter cosmological Millennium Simulation. This allowed us to analyze the MAHs of CGs and FGs and explore the connection between the two classes of groups. Our major conclusions from the analyses can be summarized as follows.

1. As many as ∼18% of fossils in the Millennium 3D catalog do not meet the fossil criteria in the mock catalog because of projection effects.

2. Fossils are older than CGs, since by z = 1, fossils have assembled more than ~55% of their z = 0 halo mass, compared to only ~40% for z = 1 CGs (Figure 3).

3. The mass accretion history of CGs in the mass range 13 < log(M/M⊙) < 13.5 is very similar to that of control groups, but in the halo-mass range of 13.5 < log(M/M⊙) < 14, it is more similar to the corresponding evolution of fossil groups. However, in general it seems that CGs follow the FG evolution more closely than they follow that of the control groups (Figure 6).

4. CGs and FGs both show trends of halo concentration slightly decreasing with halo mass, but, at a given halo mass, the concentrations of CGs are roughly 10% lower than those of FGs (Figure 8).
5. From \( z = 0.2 \) to \( z = 0 \) the angular radii of the inner and outer circles of the isolation annuli around the groups are compressed by a factor of 1.5 with time. This “compression” of CGs comes with a dimming of their luminosities, with their surface brightnesses only slightly dimming with time (Figure 9).

6. Finally, while as many as 3/4 of FGs have appeared compact since \( z = 1 \), most of these compact systems fail the compact group isolation criterion, and hence are not truly CGs as defined here, leaving only \( \sim 23\% - 36\% \) of fossils that meet the CG criteria between \( z = 1 \) and \( z = 0 \). Therefore, CGs and FGs are not intimately related classes of groups of galaxies.

7. The magnitude gap in CGs selected at \( z = 1 \) increases exponentially in time (Figure 11), but takes \( \sim 10 \) Gyr to grow to 2 mag on average. This explains why only a minority of CGs (41%) turn into FGs at \( z = 0 \).

It therefore seems that CGs constitute a specific class of groups, rather than being part of the general evolutionary path of groups that may lead to the formation of fossils. Our future work will focus on the observational properties of CGs and FGs using current galaxy surveys. Our aim will be to understand any possible link between CGs and FGs.

We thank Dr. Eugenia Díaz-Giménez for her guidance and useful discussions. The Millennium Simulation used in this paper was carried out by the Virgo Supercomputing Consortium at the Computing Centre of the Max-Planck Society in Garching. The semi-analytic galaxy catalog (De Lucia & Blaizot 2007) is publicly available at http://gavo.mpa-garching.mpg.de, and we thank Gabriela De Lucia and Jeremy Blaizot for allowing public access for the outputs of their very impressive semi-analytical models of galaxy formation. This research made use of the “K-corrections calculator” service (Chilingarian et al. 2010) available at http://kcor.sai.msu.ru.

References

Arp, H. 1966, ApJS, 14, 1
Barnes, J. 1989, MNRAS, 234, 379
Barnes, J. E. 1990, Nature, 344, 379
Barnes, J. E. 1989, Nature, 338, 123
Chandrasekhar, S. 1943, ApJ, 97, 255
Chilingarian, I. V., Melchior, A.-L., & Zolotukhin, I. Y. 2010, MNRAS, 405, 1409
Coenda, V., Muriel, H., & Martínez, H. J. 2012, A&A, 543, A119
Cole, S., Aragon-Salamanca, A., Frenk, C. S., Navarro, J. F., & Zepf, S. E. 1994, MNRAS, 271, 781
Cui W., Springel, V., Yang, X., De Lucia, G., & Borgani, S. 2011, MNRAS, 416, 2997
Dariush, A., Khosroshahi, H. G., Ponman, T. J., et al. 2007, MNRAS, 382, 433
Dariush, A., Raychaudhury, S., Ponman, T. J., et al. 2010, MNRAS, 405, 1873
De Lucia, G., & Blaizot, J. 2007, MNRAS, 375, 2
Desjardins, T. D., Gallagher, S. C., Tzanavaris, P., et al. 2013, ApJ, 763, 121
Diervila, A., Geller, M. J., & Ramella, M. 1994, AJ, 107, 868
Díaz-Giménez, E., & Mamon, G. A. 2010, MNRAS, 409, 1227
Díaz-Giménez, E., Mamon, G. A., Pacheco, M., Mendes de Oliveira, C., & Alonso, M. V. 2012, MNRAS, 426, 296
Duarte, M., & Mamon, G. A. 2015, MNRAS, 453, 3848
Dubinski, J. 1998, ApJ, 502, 141
Font, A. S., Bower, R. G., McCarthy, I. G., et al. 2008, MNRAS, 389, 1619
Fuse, C., & Broming, E. 2013, ApJL, 764, 175
Gisler, G. R. 1980, AJ, 85, 623
Gozaliasl, G., Finkelsteina, A., Khosroshahi, H. G., et al. 2014, A&A, 566, A140
Heiligman, G. M., & Turner, E. L. 1980, ApJ, 242, 532
Hickson, P. 1982, ApJ, 255, 382
Hickson, P., Mendes de Oliveira, C., Huchra, J. P., & Palmumbo, G. G. 1992, ApJ, 399, 353
Hickson, P., Richstone, D. O., & Turner, E. L. 1977, ApJ, 213, 323
Hickson, P., & Rood, H. J. 1988, ApJL, 331, L69
Jones, L. R., Ponman, T. J., Horton, A., et al. 2003, MNRAS, 343, 627
Kauffmann, G., White, S. D. M., & Guiderdoni, B. 1993, MNRAS, 264, 201
Lee, B. C., Allam, S. S., Tucker, D. L., et al. 2004, AJ, 127, 1811
Mamon, G. A. 1986, ApJ, 307, 426
Mamon, G. A. 1987, ApJ, 321, 622
Mamon, G. A. 1989, A&A, 219, 98
Mamon, G. A. 2000, in ASP Conf. Ser. 209, Small Galaxy Groups, ed. M. J. Valtonen & C. Flynn (San Francisco, CA: ASP), 217
Mamon, G. A. 2007, in Groups of Galaxies in the Nearby Universe, ed. I. Saviane, V. D. Ivanov, & J. Borrissova (Berlin: Springer), 203
Mamon, G. A. 2008, A&A, 486, 113
Mamon, G. A., & Lokas, E. L. 2005, MNRAS, 362, 95
Martínez, H. J., Coenda, V., & Muriel, H. 2013, A&A, 557, A61
McConnachie, A. W., Ellison, S. L., & Patton, D. R. 2008, MNRAS, 387, 1281
McConnachie, A. W., Patton, D. R., Ellison, S. L., & Simard, L. 2009, MNRAS, 395, 255
Mendel, J. T., Ellison, S. L., Simard, L., Patton, D. R., & McConnachie, A. W. 2011, MNRAS, 418, 1409
Moles, M., del Olmo, A., Perea, J., et al. 1994, A&A, 285, 404
Mulchaey, J. S., & Zabludoff, A. I. 1999, ApJ, 514, 133
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Neto, A. F., Gao, L., Bett, P., et al. 2007, MNRAS, 381, 1450
Ponman, T. J., Allan, D. J., Jones, L. R., et al. 1994, Natur, 369, 462
Ponman, T. J., Bourner, P. D. J., Ebeling, H., & Böhringer, H. 1996, MNRAS, 283, 690
Prada, F., Klypin, A. A., Cuesta, A. J., Betancort-Rijo, J. E., & Primack, J. 2012, MNRAS, 423, 3018
Rose, J. A. 1977, ApJL, 211, 311
Schneider, D. P., & Gunn, J. E. 1982, ApJ, 263, 14
Smith, G. P., Khosroshahi, H. G., Dariush, A., et al. 2010, MNRAS, 409, 169
Sohn, J., Hwang, H. S., Lee, M. G., Lee, G.-H., & Lee, J. C. 2013, ApJ, 771, 106
Springel, V., White, S. D. M., Jenkins, A., et al. 2005, Natur, 435, 629
Springel, V., White, S. D. M., Tormen, G., & Kauffmann, G. 2001, MNRAS, 328, 726
Stephan, M. 1877, MNRAS, 37, 334
Tormen, G., Mendes de Oliveira, C., Platen, H., Amram, P., & Ebinat, B. 2013, MNRAS, 432, 3085
Tovmassian, H., Plionis, M., & Torres-Papaqui, J. P. 2006, A&A, 456, 839
Vorontsov-Velyaminov, B. A. 1959, Atlas and Catalog of Interacting Galaxies (Berlin: Springer)
Vorontsov-Velyaminov, B. A. 1977, A&AS, 28, 1
Walke, D. G., & Mamon, G. A. 1989, A&A, 225, 291
Wechsler, R. H., Bullock, J. S., Primack, J. R., Kravtsov, A. V., & Dekel, A. 2002, ApJ, 568, 52