THE COMPACT GROUP–FOSSIL GROUP CONNECTION: OBSERVATIONS OF A MASSIVE COMPACT GROUP AT \( z = 0.22 \)\(^1 \)

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ABSTRACT

It has been suggested that fossil groups could be the cannibalized remains of compact groups that lost energy through tidal friction. However, in the nearby universe, compact groups that are close to the merging phase and display a wealth of interacting features (such as HCG 31 and HCG 79) have very low velocity dispersions and poor neighborhoods, unlike the massive, cluster-like fossil groups studied to date. In fact, known \( z = 0 \) compact groups are very seldom embedded in massive enough structures that may have resembled the intergalactic medium of fossil groups. In this Letter, we study the dynamical properties of CG 6, a massive compact group at \( z = 0.220 \) that has several properties in common with known fossil groups. We report on new \( g' \) and \( i' \) imaging and multislit spectroscopy performed with GMOS on Gemini South. The system has 20 members within a radius of 1 \( h^{-1} \) Mpc, a velocity dispersion of 700 km s\(^{-1}\), and a mass of \( 1.8 \times 10^{14} \ M_\odot \), similar to that of the most massive fossil groups known. The merging of the four central galaxies in this group would form a galaxy with magnitude \( M_r \sim -23.4 \), typical for first-ranked galaxies of fossil groups. Although nearby compact groups with similar properties to CG 6 are rare, we speculate that such systems occurred more frequently in the past and may have been the precursors of fossil groups.

Subject headings: galaxies: clusters: individual (HCG 31, HCG 79, HGC 92, SDSS CG 6) — galaxies: kinematics and dynamics — galaxies: structure

1. INTRODUCTION

Groups of galaxies are small systems of typically a few \( L^\ast \) galaxies, which comprise over 55\% of the nearby structures in the universe. A small fraction of galaxy groups are classified as compact groups (CGs), which are responsible for \( \sim 1\% \) of the luminosity density of the universe (Mendes de Oliveira & Hickson 1991). Although they are rare objects in the nearby universe, their high galactic densities and low velocity dispersions make them ideal systems for the study of galaxy transformation through galaxy-galaxy collisions. As expected, these systems have a high fraction of interacting members, although merged objects are rare (Zepf 1993). They are commonly believed to evolve through dynamical friction and finally merge to form a single galaxy (Barnes 1992). Vikhlinin et al. (1999) and Jones et al. (2003) have suggested that the merging of CGs can lead to the formation of fossil groups (FGs). A FG is a system with an extended and luminous X-ray halo \( (L_X > 10^{43} \ h^{-3} \ ergs \ s^{-1}) \), dominated by one single brighter than \( L^\ast \) elliptical galaxy, surrounded by low-luminosity companions (where the difference in magnitude between the bright dominant elliptical and the next brightest companion is \( >2 \) mag in the \( R \) band; Jones et al. 2003).

One important goal of this Letter is to investigate if CGs, as we know them today, could be the precursors of FGs. In order to answer this question, we summarize, in § 2, the properties of a few of the most strongly interacting nearby CGs known, which are about to merge, and in § 3, we describe the properties of the five FGs that have been studied spectroscopically so far. In § 4, we present new observations for a CG embedded in a cluster-size potential, at redshift \( z = 0.22 \), and § 5 puts together all the observations described and discusses the CG-FG scenario. Throughout this Letter, we adopt when necessary a standard cosmological model: \( H_0 = 70 \ h^{-1} \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_m = 0.3 \), and \( \Omega_{\Lambda} = 0.7 \). At \( z = 0.22 \), 1'' corresponds to \( 3.5 \ h^{-1} \) kpc.

2. INTERACTING COMPACT GROUPS: HCG 31, HCG 79, AND HCG 92

There is evidence from both observations and simulations that groups evolve through dynamical friction and coalesce to form more compact structures as the universe ages. A few of the most compact, and therefore most evolved, groups known from Hickson’s catalog (Hickson et al. 1992) are HCG 31, HCG 79 (or Seyfert Sextet), and HCG 92 (or Stephan’s quintet). The study of these groups is important to help understand processes common in merging systems, environments that may have occurred more often in the high-redshift universe.

HCG 31 is a group at \( z \sim 0.013 \) and with a velocity dispersion of \( \sigma \sim 60 \) km s\(^{-1}\). This is a gas-rich group with intense star-forming activity (e.g., Mendes de Oliveira et al. 2006b; Amram et al. 2007), dominated by a central pair of interacting dwarf galaxies A+C. HCG 31 is thought to be in a premerging phase (Amram et al. 2004; Verdes-Montenegro et al. 2005), and it has well-developed tidal tails seen in \( H\alpha \) and H \( \alpha \). The group hosts two excellent candidates for tidal dwarf galaxies, namely, member F; in the southern tail, and member R, 50 \( h^{-1} \) kpc to the north of the group (for an assumed distance modulus \( DM = 33.8 \)).

HCG 79, also known as Seyfert Sextet, was originally identified as a sextet of galaxies, but it is now known to be a quartet at \( z = 0.0145 \) (the fifth object is in the background, and the sixth is luminous tidal debris to the northeast of the group). This is the largest CG in Hickson’s catalog, with a galaxy-galaxy distance below 10 kpc (for an adopted DM = 34.0) and a velocity dispersion of \( \sigma = 138 \) km s\(^{-1}\). The four galaxies present...
morphological distortions and increased activity (tidal debris, bar in HCG 79B, dust lane in HCG 79A, radio and infrared emission, disturbed rotation curves, and nuclear activity). The group presents a prominent intragroup light envelope that contains 45% of the total light of the group (Da Rocha & Mendes de Oliveira 2005) and irregular envelopes of H/II (Williams et al. 1991) and X-rays (Pildis et al. 1995). These suggest that recent or ongoing interaction is taking place within this system.

HCG 92, also known as Stephan’s quintet, is in reality a quartet with $z = 0.0215$ and a foreground galaxy. It is the best-studied CG—multiwavelength data are available from radio to X-rays. Most of the gaseous material in Stephan’s quintet is concentrated not in the galaxies but in the intragroup medium, suggesting that collisions among group members may have happened frequently. A number of tidal dwarf galaxies and intergalactic H II regions have been identified in this group (e.g., Mendes de Oliveira et al. 2001, 2004; Xu et al. 2005). Of the three groups described above, HCG 92 is the only one to have detected X-rays, with a total bolometric luminosity of $2.96 \times 10^{37} \text{ergs s}^{-1}$ (Xue & Wu 2000).

These three spiral-rich groups are thought to be in their final stages of evolution—they are, in fact, some of the most compact systems found in Hickson’s catalog. Yet, they have members that can be clearly identified as individual galaxies, suggesting that once merging starts, it may proceed quickly, and the groups may no longer be recognized as such. The bright members of these groups will almost certainly end up as a single galaxy pile. A discussion of whether these systems will most likely end up as FGs or as single isolated elliptical galaxies is deferred to § 5. In § 3, some of the optical properties of the FGs studied so far are summarized.

3. DYNAMICAL PROPERTIES OF FGs

Only five FGs have been studied so far in any level of detail in the optical bands (imaging and spectroscopy).

Mendes de Oliveira et al. (2006a) derived the physical properties of the FG RX J1552.2±2013, at a redshift of $z = 0.136$, and computed its luminosity function, based on the spectroscopy of 36 member galaxies. This system was found to be a fossil cluster, given its high number of members and high velocity dispersion (close to 700 km s$^{-1}$).

Cypriano et al. (2006) studied a second FG, RX J1416.4±2315, at a similar redshift of $z = 0.137$. For this system also, a fairly high velocity dispersion was measured ($584 \text{ km s}^{-1}$), for 25 members located in the inner $542 \, h_{70}^{-1} \, \text{kpc}$ ($0.45$ of the virial radius) of the system. Similar results were found by Khosroshahi et al. (2006).

In two recent studies (C. L. Mendes de Oliveira et al. 2008, in preparation; E. S. Cypriano et al. 2008, in preparation), two other FGs were also found to have cluster-like masses: RX J1340.5±4017, with 25 members, was found to have a velocity dispersion of 580 km s$^{-1}$, and for RX J1256.0±2556, a velocity dispersion of 582 km s$^{-1}$ was determined from spectroscopy of 28 members. In all four cases, the systems presented very pronounced red sequences in their color-magnitude diagrams and they were dominated by early-type galaxies. Table 3 of Khosroshahi et al. (2006) lists one other FG for which spectroscopy for a significant number of members has been obtained: ESO 3060170, which is found to have a velocity dispersion of $648 \, h_{70}^{-1} \, \text{km s}^{-1}$ derived from velocity measurements of 15 members.

The conclusion is then that all five groups studied so far for which more than six members are known have velocity dispersions of $\sim 600 \, h_{70}^{-1} \, \text{km s}^{-1}$ or higher and dynamical virial masses $\sim 10^{14} \, h_{70}^{-1} \, M_\odot$. FGs were suggested to be the end products of merging of L* galaxies in low-density environments (Jones et al. 2003).

However, the five FGs studied do not constitute low-density environments and, in fact, are more similar to galaxy clusters. The fairly high X-ray emission, the large fraction of elliptical galaxies, as well as the lack of obvious substructures, suggest that these FGs are fairly massive virialized systems.

The FGs described above have masses, kinematics, and environments that are very different from those of nearby CGs. At first sight, this evidence would seem to indicate that there is no connection between these two kinds of systems. However, before discussing this point any further, we present in § 4 an example of a CG that does have similar optical properties to those of FGs. It is the farthest away CG known to date, at $z = 0.22$. New imaging and spectroscopic observations of this group are presented in § 4. A detail description of the properties of CG 6 will be presented in a future paper (E. R. Carrasco et al. 2008, in preparation).

4. CG 6: A COMPACT GROUP AT $z = 0.22$

CG 6 is a group from the Lee et al. (2004) catalog of CG galaxies, chosen from the SDSS database. Before the present study, only one galaxy in the system, the central one, had a measured redshift. The observations of SDSS CG 6 were carried out using the Gemini Multiobject Spectrograph (Hook et al. 2004) at the Gemini South telescope.

The group was imaged using the standard g’ and i’ filters (Fukugita et al. 1996) on 2005 December 1. Exposures of $3 \times 150 \, \text{s}$ in the g’ and $3 \times 120 \, \text{s}$ in the i’ filter, under photometric conditions, were obtained. The images were observed with median seeing values of 0.73” and 0.55” in the g’ and i’ filters, respectively, Figure 1 shows the color composite image of the SDSS CG 6 group. All galaxies with measured radial velocities are marked (see below).
All observations were processed with the Gemini IRAF package version 1.8 inside IRAF\textsuperscript{2} in a standard way. Calibrations of the magnitudes to the standard system were derived using observations of standard stars from Landolt (1992) field RU149.

Object detection and photometry were performed on the $i$-band image with the SExtractor program (Bertin & Arnouts 1996). MAGAUTO was adopted as the total magnitude. Colors were derived by measuring fluxes inside a fixed circular aperture of 24 pixels ($1.75\,\text{arcsec}$) in both filters, corresponding to a physical aperture of 6.2 $h_{70}\,\text{kpc}$ at the rest frame of the group. All objects with SExtractor stellarity flag $\leq 0.85$ were selected as galaxies. We estimate that the catalog is complete down to $i' = 23.5\,\text{mag}$, since the number counts start to turn over at this value. The final catalog contains the total magnitudes, colors, and structural parameters for 409 galaxies brighter than $i' = 23.5\,\text{mag}$ (at the distance of the group, with no $k$-correction).

Galaxies for spectroscopic follow-up were selected on the basis of their magnitudes and colors. Figure 2 shows the color-magnitude diagram for galaxies with $i' \leq 23\,\text{mag}$. A pronounced red sequence is readily seen. Objects in the region below the red cluster sequence (solid line) and brighter than $i' = 21\,\text{mag}$ ($M_r \sim -16.7\,\text{mag}$ at the distance of the group, with no $k$-correction) are selected as potential candidates of the system.

Galaxy spectra were observed in 2005 December, during dark time, with relatively good transparency and with a seeing that varied between 0.9$''$ and 1.0$''$. Three exposures of 1400 s were obtained through a mask with 1.0$''$ slits, using the 400 line mm$^{-1}$ ruling density grating (R400) and centered at 6300 Å, for a resolution of 8 Å. Reduction and calibration of the data were done in the standard way, using the Gemini IRAF package version 1.8.

We were able to measure redshifts for 35 observed galaxies using cross-correlation techniques and emission-line fitting. Twenty-two of the galaxies are located at the redshift of the group (within $\pm 2000\,\text{km s}^{-1}$ and in the range $0.213 < z < 0.226$). We used the ROSTAT program (Beers et al. 1990) to calculate the average velocity and the one-dimensional line-of-sight velocity dispersion of the group. We found that the group is located at $z = 0.21981 \pm 0.00054$, with a velocity dispersion of $\sigma = 703 \pm 103\,\text{km s}^{-1}$ and with 20 member galaxies. Figure 3 shows the velocity distribution of the 20 galaxies at the redshift of the group.

We used the same software to do a statistical analysis of the velocities, and we found no large gap in the velocity distribution, which closely follows a Gaussian shape. The virial mass computed using the 20 galaxies with concordant redshifts, for a distance modulus of 40.18, is $M_{\text{vir}} = 1.77_{-0.21}^{+0.45} \times 10^{14}\,h_{70}^{-1}\,M_\odot$, and the virial radius is $R_{\text{vir}} = 0.82_{-0.01}^{+0.02} h_{70}^{-1}\,\text{Mpc}$ (the errors are 68$\%$ confidence intervals).

We checked for any significant effects in the velocity dispersion and total mass of the system when we exclude the emission-line galaxies from the sample. For this smaller sample, we obtained a lower velocity dispersion of $\sigma = 608 \pm 99\,\text{km s}^{-1}$, a virial mass of $M_{\text{vir}} = 0.95_{-0.32}^{+0.52} \times 10^{14}\,h_{70}^{-1}\,M_\odot$, and a virial radius $R_{\text{vir}} = 0.64_{-0.11}^{+0.18} h_{70}^{-1}\,\text{Mpc}$ (again the errors are 68$\%$ confidence intervals), values not significantly different from those considering the whole sample. The results go in the direction of what was previously seen also for other systems: inclusion of the emission-line galaxies enhance the velocity dispersion of the system.

5. DISCUSSION

Dynamical friction and subsequent merging are probably the processes responsible for the lack of L* galaxies in FGs. Considering the merging scenario, it is possible that the overluminous central galaxy in a FG has been formed within a substructure,
inside a larger structure. In that case, one could think of a scenario where a CG was formed within a rich group, which would then have merged, leaving behind the brightest elliptical galaxy of what today is seen as a FG. One weak argument against this scenario is that the nearby examples of CGs are not usually found within such massive structures but instead are more often surrounded by very sparse structures. There are, however, examples such as CG 6, surrounded by large numbers of lower luminosity galaxies, inhabiting a deep potential well.

We would like to test the hypothesis that CGs, as observed in the nearby universe, could be the precursors of FGs. We may examine two aspects: (1) if the sum of the luminosities of the brightest CG galaxies is similar to the luminosity of a first-ranked FG galaxy and (2) if the neighborhoods of CGs are rich, i.e., if the system as a whole (group plus environment) has a velocity dispersion/mass similar to that of a FG.

We compute the total luminosity of the galaxies in the soon-to-merge CGs HCG 31, HCG 79, and HCG 92, to check how these compare with the luminosities of first-ranked galaxies in FGs. Adding up the luminosities of galaxies HCG 31 A to C, G, and Q, which are the brightest in the group HCG 31, a magnitude of $M_B = -22.5$ is obtained (for $DM = 33.8$). Summing up the luminosities of galaxies HCG 79 A–D, an equal total magnitude of $M_B = -22.5$ is obtained (for $DM = 34.0$). These are upper limits on the luminosities of these objects given that several members are starburst galaxies. After fading, the merged central objects in HCG 31 and HCG 79 will have somewhat lower magnitudes than that of a typical first-ranked galaxy in a FG. FGs’ first-ranked galaxies have luminosities well above $L^*$, for the five FGs studied by Jones et al. (2003), the first-ranked galaxies had a median luminosity of $M_B = -23.2$, and for the 34 FGs found in the SDSS DR5 by dos Santos et al. (2007) the median luminosity was $M_B = -23.5$.

Although for HCG 92, the final object (adding up luminosities of galaxies A–E) would have an absolute magnitude of $M_B = -24.2$ (for $DM = 34.8$), which after allowing for some fading could be similar to that of a FG first-ranked galaxy, HCG 92 would possibly still not resemble a FG when merged, because its neighborhood is very sparse; i.e., it is not embedded in any larger structure, as is often the case for the central galaxy in FGs. This is in agreement with its relatively low bolometric X-ray luminosity of $2.96 \times 10^{42} h_{70}^{-2} \text{erg s}^{-1}$ (Xue & Wu 2000).

The environments of nearby CGs have been surveyed by Ribeiro et al. (1998), Zabludoff & Mulchaey (1998), and Carrasco et al. (2006), among others. Spectroscopy of dozens of members in the neighborhood of quite a number of groups was obtained, confirming in all cases that CGs have low velocity dispersions typical of the group regime (typically $200–300 \text{ km s}^{-1}$). In fact, even for HCG 62, thought to be one of the most massive CGs in Hickson’s catalog, the velocity dispersion obtained from 45 members of the system showed that it is a bona fide group ($376 \text{ km s}^{-1}$). HCG 62 was suggested by Ponman & Bertram (1993) as an example of a system that could turn into a FG in a few gigayears, but its velocity dispersion is still much lower than the value of $\sim 600 \text{ km s}^{-1}$, typical for rich FGs. Two other massive nearby CGs in Hickson’s catalog are HCG 94 and HCG 65. The first is known to have a very high bolometric X-ray luminosity of $2.35 \times 10^{44} h_{70}^{-2}$ (Xue & Wu 2000), which may, however, be contaminated by the emission of a nearby cluster. The velocity dispersion obtained from 11 members in this system gives a value of $479 \text{ km s}^{-1}$. HCG 65 is the center of the cluster Abell 3559. It is in the heart of the Shapley supercluster, and its location makes it hard to disentangle its dynamics and determine its mass. The three most massive Hickson CGs known—HCG 62, HCG 65, and HCG 94—are strongly early-type-dominated, as expected from the velocity dispersion–morphology relation observed for CGs.

The conclusion is then that a typical CG, as observed at $z = 0$, is unlikely to turn into a FG. It is more likely to merge into an isolated elliptical galaxy. For CG 6, at $z = 0.22$ and $\sigma = 703 \text{ km s}^{-1}$, if we merge the four central galaxies (A, B, C, and D), we end up with a galaxy with total magnitude $i' = 16.31$ and $g' = 17.80 \text{ mag}$ ($M_g = -23.87$ and $M_g = -22.38$, with no $k$-correction). If we use the color relation for a galaxy at $z = 0.2$ from Fukugita et al. (1995), the magnitude in $r'$ will be $16.83$ or $M_r = -23.35$. This magnitude is similar to those of typical central galaxies in FGs, and the velocity dispersion of the system is typical for the studied FGs. However, no gap of at least 2 mag between the first-ranked relic and the remaining objects of the system would be observed because there is at least one other bright galaxy in the system within half the virial radius of the group. We point out that one other example of a possible massive system, at $z = 0.39$, which may turn into a FG, has recently been discovered by Rines et al. (2007). Spectroscopic studies of CGs at medium redshifts may find many more of such objects.

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