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A UNIONS VIEW OF THE BRIGHTEST CENTRAL GALAXIES OF CANDIDATE FOSSIL GROUPS

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Abstract.
The formation process of fossil groups (FGs) is still under debate, and large samples of such objects are missing. With the aim to increase the sample of known FGs, analyse the properties of their brightest group galaxies (BGGs), and compare them with a control sample of non-FG BGGs, we extracted a sample of 87 FG and 100 non-FG candidates from a large spectroscopic catalogue. For all the objects with data available in UNIONS (initially the Canada France Imaging Survey, CFIS) in the u and r bands, and/or in an extra r-band processed to preserve all low-surface-brightness features (rLSB), we performed a 2D photometric fit of the BGG with GALFIT with one or two Sérsic components. We also analysed how the subtraction of the intracluster light (ICL) contribution modifies the BGG properties. From the SDSS spectra available for the BGGs of 65 FGs and 82 non-FGs, we extracted the properties of their stellar populations with Firefly.

We find that morphologically, a single Sérsic profile can fit most objects in the u band, while two Sérsics are needed in the r and rLSB bands, both for FGs and non-FGs. Non-FG BGGs cover a larger range of Sérsic index n. FG BGGs follow the Kormendy relation (mean surface brightness versus effective radius) previously derived for almost 1000 brightest cluster galaxies (BCGs), while the majority of non-FG BGGs are located below this relation, with fainter mean surface brightnesses. This suggests that FG BGGs have evolved similarly to BCGs, while non-FG BGGs have evolved differently. The above properties can be strongly modified by the subtraction of the ICL contribution. On the other hand, based on spectral fitting, the stellar populations of FG and non-FG BGGs do not differ significantly.

Keywords: fossil groups, brightest group galaxies

1 Introduction

Fossil groups (FGs) were discovered by Ponman et al. (1994). They are particular groups of galaxies with high X-ray luminosities but with fewer bright galaxies than most groups or clusters of galaxies. Jones et al. (2003) later provided a commonly accepted definition of FGs based on three conditions: their X-ray luminosity is at least $L_X = 10^{42}\ h_{50}^{-2}$ erg s^{-1}, their brightest group galaxy (BGG) is two magnitudes brighter than other group members, and the distance between the two brightest galaxies is smaller than half the group virial radius. The formation mechanism of FGs is still under debate: they can be the remnants of early mergers, or be a short temporary stage of group evolution.

Adami et al. (2020) carried out a statistical study of FGs, based on photometric redshifts, and concluded that FGs were most probably in a poor environment. Several studies have shown that the role of the BGG is

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crucial to explain the lack of bright galaxies in FGs. We gathered a large sample of candidate FGs from the groups detected by Tinker* from SDSS data, aiming to increase the number of known FGs, analyse the physical properties of the BGGs of FGs and compare them to those of non-FGs and clusters.

2 The sample, data and method

Tinker has made catalogues available that contain data for 559,038 galaxies, providing positions, spectroscopic redshifts from the SDSS survey, k-corrected and evolution-corrected (to z=0.1) g and r band absolute magnitudes, galaxy stellar masses, and total halo masses. For each galaxy, the group to which it belongs is indicated.

We eliminated all the galaxies that were alone in a group and obtained a catalogue of 201,007 galaxies that were at least in a pair. We then selected the galaxies belonging to groups where the magnitude difference in the r band between the brightest and second-brightest galaxy was at least 2 mag, and for which the distance between these two galaxies was smaller than half the virial radius, r_{vir}. We thus obtained a catalogue of 2453 galaxies.

From the above catalogue, we extracted a list with the brightest galaxy of each group, and this led to a catalogue of 1112 galaxies that may be considered as BGGs. This means that most groups were made of pairs. In order to avoid considering objects that could not be real groups, such as isolated galaxies with a few small satellites, we added a condition on the halo mass: $M_{halo} > 10^{13}$ M$_{\odot}$, giving 87 FG candidates. We note that for most of these FGs we have no X-ray information, so they are FG candidates.

In order to compare the properties of BGGs of FGs with those of non-FGs, we built a catalogue of non-FGs in a similar way, but imposing a magnitude difference between the brightest and second-brightest galaxies smaller than 2. This condition, together with that of $M_{halo} > 10^{13}$ M$_{\odot}$, gave 100 non-FG candidates.

Most of the FGs are in the [0.02,0.12] redshift range, with only five FGs in the [0.12,0.18] range.

We searched for images of the 87 FG candidates in the UNIONS image database (DR3) in the u and r bands. Images were retrieved from the DR3. We found images for 35 FGs in the u band and for 25 FGs in the r band, among which 12 FGs having both u and r band images. We also retrieved UNIONS images in the u, r, and rLSB bands for a subsample of 30 non-FGs.

Chu et al. (2022) showed that subtracting the contribution of intracluster light (ICL) could modify the properties derived for BCGs. Therefore, with the aim of estimating how subtracting the ICL could modify the properties derived for the BGG, we also exploited the r band images processed to preserve all low-surface-brightness (LSB) features (hereafter referred to as rLSB). These images were obtained using an observing technique that is optimised for LSB surveys at CFHT.

The 2D profile of each BGG was fit with GALFIT (Peng et al. 2002) with a single Sérsic model and with a double Sérsic model. GALFIT initial parameters were obtained with SExtractor using a bulge + disk model. A mask and a point spread function were created following the method described in Chu et al. (2021). The choice between a single and double Sérsic model was made based on the statistical F-test (Margalef-Bentabol et al. 2016) and the computed p-value, which indicates whether or not complexifying the model is necessary by increasing the number of degrees of freedom. As the current sample has the same resolution as that of Chu et al. (2022), we adopt the same p-value limit to distinguish between the two different models: $P_0 = 0.15$.

3 Morphological properties of the BGGs

Table 1. 2D profile model distribution of BGGs of FGs and non-FGs.

	FG				Non-FG			
	u	r	rLSB	rLSB-ICL	u	r	rLSB	rLSB-ICL
One-Sérsic	29	2	9	3	27	6	14	6
Two-Sérsic	6	23	10	16	3	24	16	24

The numbers of BGGs of FGs and non-FGs for which one Sérsic law (S1) or two Sérsic laws (S2) are needed to fit their 2D profiles in the various bands are given in Table 1. For FGs, we can see that in the u band, most BGGs can be fit with a single Sérsic (83%). In contrast, a major part of the profiles in the r band require two

*https://www.galaxygroupfinder.net/catalogs components (92%). If we now consider the BGGs from the rLSB data, only 53% require two Sérsics. Comparable results are obtained for non-FG BGGs, and the difference between FGs and non-FGs is not significant in view of the dispersion.

We computed the ICL contribution and subtracted it from the BGGs to see how the Sérsic parameters changed. If we look at Table 1, we can see that only 3 FG BGGs out of 19 (16%) can be fit with a single Sérsic, and for non-FG BGGs, 6 out of 30 BGGs (20%) are fit with a single Sérsic. The subtraction of the ICL contribution therefore does not make the second Sérsic component disappear, as already observed by Chu et al. (2022). Unexpectedly, we find more BGGs of FGs and non-FGs that are better modelled by two-Sérsic profiles on ICL-subtracted rLSB images than on rLSB images.

The only clear difference that we find between the physical properties of FGs and non-FGs is that FG BGGs are intrinsically brighter. This may be due to a selection bias, as our sample of FG BGGs is overall brighter than our sample of non-FG BGGs, but may indicate that, in a given group-mass range, FG BGGs are indeed brighter and most of the mass of the group is concentrated in the BGG.

A full discussion of these properties can be found in Chu et al. (2023).

4 Kormendy relation

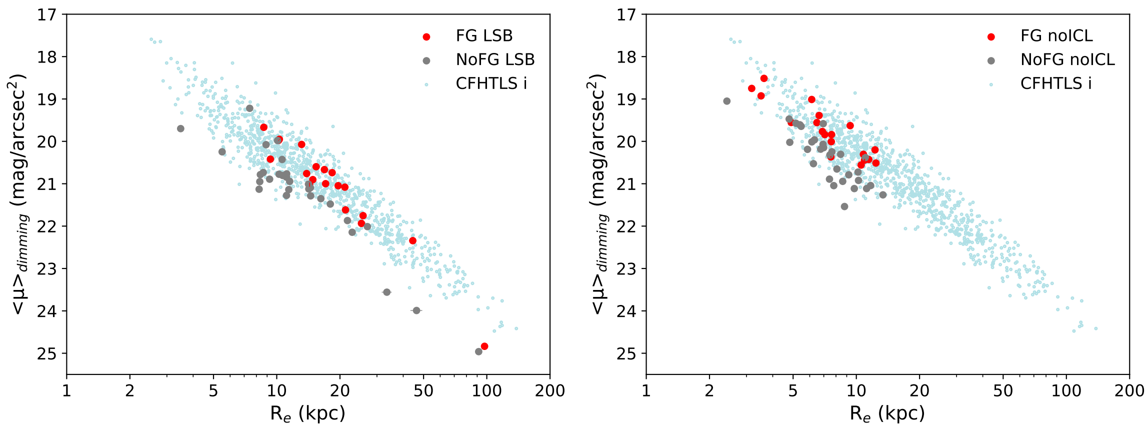

Fig. 1. Kormendy relation for FGs in red and Non-FGs in grey, superimposed on the relation found for almost one thousand BCGs by Chu et al. (2022) in cyan. Both plots are obtained in the rLSB band, the left plot without ICL subtraction and the right plot after ICL subtraction. The points for FGs and non-FGs have been shifted from the r to the i band, and all points are corrected for cosmological dimming.

We now consider the relation found by Kormendy (1977) (mean effective brightness $<\mu>$ as a function of effective radius R_e), which can be fit with the following law:

$$<\mu>= (a \pm \sigma_a) \times log(R_e) + (b \pm \sigma_b).$$

We find the dispersion to be smaller for FGs than for non-FGs in all bands, and the relations in u and r are parallel within the dispersion. With the exception of the rLSB band, the slopes are larger for non-FGs than for FGs, but in view of the dispersion this difference is not significant.

If we compare the Kormendy relations found here for FGs and non-FGs to those of Chu et al. (2022), we see that FGs are located on this relation, while the majority of non-FGs are located below the relation, and this is true both before and after ICL subtraction.

The BGGs of FGs appear to have properties more similar to those of BCGs than to those of non-FG BGGs, suggesting that BGGs in FGs and BCGs have followed a comparable evolutionary path, while non-FGs have evolved somewhat differently, reaching fainter surface brightnesses.

5 Influence of the ICL contribution

We compared the values of the various physical parameters galaxy by galaxy before and after ICL subtraction. The ICL contribution was estimated with `DAWIS` (Detection Algorithm with Wavelets for Intracluster light

Studies; Ellien et al. 2021), a wavelet-based algorithm optimised for the detection and characterisation of LSB structures in deep optical images.

For FGs, we find that the ICL increases the effective radius by a mean factor of 3.7, and the ICL adds light to the BGG by up to 1.3 mag. With ICL, the mean surface brightness can be up to 5 mag arcsec^{-2} brighter, with a mean at 1.3, and the Sérsic index n tends to be larger (by 2.8 on average). There seems to be a bimodality in the Sérsic index histogram. The peak at $n < 2$ comes from BGGs that were better modelled with two Sérsic profiles before and after ICL subtraction, and the peak at $n > 3$ originates from 1-Sérsic profile BGGs on LSB images that become 2-Sérsic BGGs after ICL subtraction.

For non-FGs, the ICL increases the effective radius by a mean factor of 2.4 and the absolute magnitude with ICL is up to 1.2 mag brighter. The mean surface brightness before subtraction of the ICL can be up to 1.2 mag arcsec^{-2} fainter, with a mean of about 0.8, and the Sérsic index n tends to be larger with ICL, with a large dispersion from one BGG to another.

When the ICL is subtracted, the Sérsic index distributions become comparable for FGs and non-FGs, and the distributions of the properties of BGGs obtained for FGs and non-FGs after ICL subtraction become more comparable to those measured in the r filter.

We can note that BGGs on r images appear bigger, brighter, with fainter mean surface brightnesses and higher Sérsic indices than on rLSB-ICL images. This illustrates the fact that ICL somewhat modifies the apparent morphological properties, and that its contribution should be carefully subtracted before analysing the physical properties of BCGs and BGGs, as already underlined by Chu et al. (2022).

6 Stellar populations of BGGs

We retrieved the spectra of the FG and non-FG BGGs of our sample in the SDSS. Among the 87 FGs, 9 spectra were not available, leaving us with 78 BGGs. Among the 100 non-FGs, 4 spectra were not available, and so we analysed 96 spectra. We fit these spectra with Firefly (Wilkinson et al. 2017) and eliminated the spectra corresponding to AGN as classified by the SDSS: 13 in FGs and 14 in non-FGs. This was done because it is difficult to extract stellar populations from spectra dominated by an AGN. The AGN fractions are very similar between BGGs of FGs and non-FGs, namely 20% and 17%, respectively. We were therefore left with 66 FG BGG and 82 non-FG BGG spectra. As Wilkinson et al. (2017) showed that Kroupa and Salpeter IMFs gave comparable results, we limited our analysis to a Kroupa IMF. We used the STELIB and MILES stellar libraries to estimate the robustness of our results.

We find that 76% and 71% of the total stellar mass of FG and non-FG BGGs, respectively, was already formed 8 Gyr ago based on the STELIB library. These percentages become 61% and 66% for the MILES library. These results agree with the fact that BGGs of FGs and non-FGs have very similar colours. The stellar populations of FG and non-FG BGGs cannot be distinguished with this relatively straightforward analysis.

7 Conclusions

Although the morphological properties of FG and non-FG BGGs somewhat differ, FG BGGs having properties comparable to those of cluster BCGs, their stellar populations do not. We emphasize the importance of taking into account the ICL contribution when analysing the morphological properties of BCGs.

References

Adami, C., Sarron, F., Martinet, N., & Durret, F. 2020, A&A, 639, A97

Chu, A., Durret, F., Ellien, A., et al. 2023, A&A, 673, A100

Chu, A., Durret, F., & Márquez, I. 2021, A&A, 649, A42

Chu, A., Sarron, F., Durret, F., & Márquez, I. 2022, A&A, 666, A54

Ellien, A., Slezak, E., Martinet, N., et al. 2021, A&A, 649, A38

Jones, L. R., Ponman, T. J., Horton, A., et al. 2003, MNRAS, 343, 627

Kormendy, J. 1977, ApJ, 218, 333

Margalef-Bentabol, B., Conselice, C. J., Mortlock, A., et al. 2016, MNRAS, 461, 2728

Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W. 2002, The Astronomical Journal, 124, 266

Ponman, T. J., Allan, D. J., Jones, L. R., et al. 1994, Nature, 369, 462

Wilkinson, D. M., Maraston, C., Goddard, D., Thomas, D., & Parikh, T. 2017, MNRAS, 472, 4297