Nuclear Activity in Galaxies Across Cosmic Time
Proceedings IAU Symposium No. 356, 2019
M. Pović, P. Marziani, J. Masegosa, H. Netzer, S. H. Negu & S. B. Tessema, eds.
doi:10.1017/S1743921320003105

The role of AGN activity in the building up of the BCG at z ∼ 1.6

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Abstract. XDCPJ0044.0-2033 is one of the most massive galaxy cluster at $z \sim 1.6$, for which a wealth of multi-wavelength photometric and spectroscopic data have been collected during the last years. I have reported on the properties of the galaxy members in the very central region ($\sim 70kpc \times 70kpc$) of the cluster, derived through deep HST photometry, SINFONI and KMOS IFU spectroscopy, together with Chandra X-ray, ALMA and JVLA radio data.

In the core of the cluster, we have identified two groups of galaxies (Complex A and Complex B), seven of them confirmed to be cluster members, with signatures of ongoing merging. These galaxies show perturbed morphologies and, three of them show signs of AGN activity. In particular, two of them, located at the center of each complex, have been found to host luminous, obscured and highly accreting AGN ($\lambda = 0.4 - 0.6$) exhibiting broad Hα line. Moreover, a third optically obscured type-2 AGN, has been discovered through BPT diagram in Complex A. The AGN at the center of Complex B is detected in X-ray while the other two, and their companions, are spatially related to radio emission. The three AGN provide one of the closest AGN triple at z > 1 revealed so far with a minimum (maximum) projected distance of 10 kpc (40 kpc). The discovery of multiple AGN activity in a highly star-forming region associated to the crowded core of a galaxy cluster at $z \sim 1.6$, suggests that these processes have a key role in shaping the nascent Brightest Cluster Galaxy, observed at the center of local clusters. According to our data, all galaxies in the core of XDCPJ0044.0-2033 could form a BCG of $M_\star \sim 10^{12} M_\odot$ hosting a BH of $2 \times 10^8 - 10^9 M_\odot$, in a time scale of the order of 2.5 Gyrs.

Keywords. galaxy cluster, BCG formation, active galaxies, galaxy formation

1. Introduction

Relaxed, virialized and undisturbed galaxy cluster in the local Universe are characterised by a bright, massive and large elliptical galaxy at their center, the so called Brightest Cluster Galaxy (BCG). The BCG is usually located at the center of the cluster potential well, close to the peak of X-ray emission. How these galaxies form is still a matter of study. According to most models, the epoch of their assembly is mostly between z=1 and z=2, where the mass of the BCG goes from 10% to 50% of the final mass. For this reason, this redshift range is crucial to observe the BCG progenitors and to witness its assembly. Indeed, the cores of galaxy clusters at $z = 1 - 2$ show a different picture compared to the local Universe, i.e. in most cases there is no single BCG, and the core is characterised by several galaxies which are typically blue, star forming and with disturbed morphology. This implies the existence of a mechanism able to drive such transformation. Interestingly, also looking at the properties of the whole galaxy cluster population, there are evidences that z=1.5 is a crucial epoch. Indeed, while at $z < 1.4$ the number of star forming galaxies (SFGs) increases towards the cluster outskirt, at $z > 1.4$ the SF activity is higher in the core of the cluster (Brodwin *et al.* 2013). For all these reasons, we studied the core of the X-ray detected galaxy cluster XDCP J0044.0-2033 (hereafter

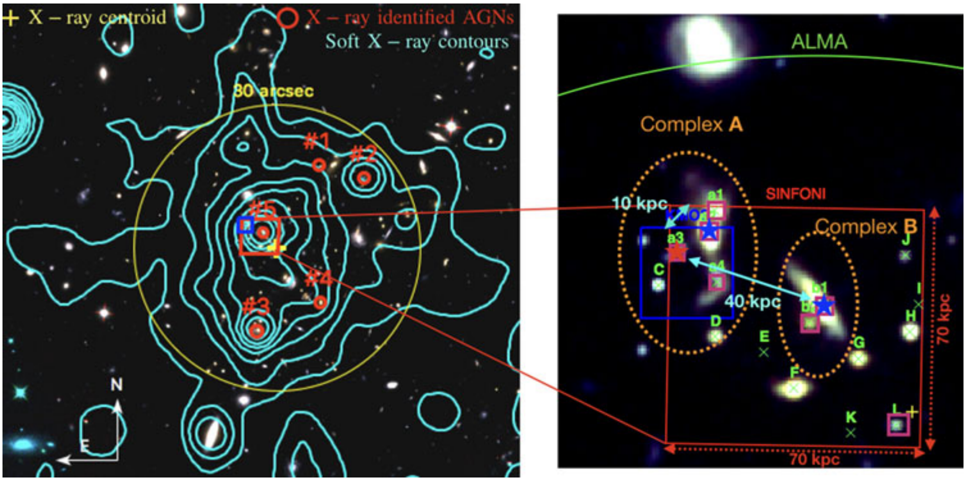

Figure 1. [Adapted from Travascio *et al.* 2020] *Left Panel:*: HST RGB (F105W + F140W + F160W) image of the galaxy cluster `XDCP0044`. The yellow cross indicates the centroid of the extended X-ray emission while the yellow circle is $R_{2500} = 250kpc$. The cyan contours are the Chandra soft $[0.5 - 2]keV$ X-ray emissions while the red circles mark the unresolved X-ray sources as identified by Tozzi *et al.* (2015). Finally, the red and blue squares delimit the region analyzed in this paper, corresponding to the SINFONI and the KMOS FOVs. *Right Panel*: zoom-in of the analyzed central region, where two complexes (A and B) are highlighted with the orange dashed line. Green crosses mark the 16 HST identified photometric sources while magenta squares mark the sources for which a spectroscopic redshift has been determined. AGN are indicated with blue (type-1) and red (type-2) stars.

XDCP0044; Santos *et al.* 2011; Fassbender *et al.* 2011) at $z \sim 1.6$. XDCP0044 is the most massive galaxy clusters ($M_{200} = 4 \times 10^{14} M_{\odot}$) discovered in the XDCP project through XMM archival data (Fassbender *et al.* 2011) and one of the most massive at $z > 1.5$. It is in a quite advanced state of dynamical relaxation, and shows a reversal SF-density relation (Santos *et al.* 2015). XDCP0044 is a unique laboratory to study the building-up of the BCG and the interplay between galaxies, nuclear activity, and the inter-galactic gas in the core of massive high redshift galaxy clusters.

Fig. 1 (left panel) shows the HST RGB (F105W+F140W+F160W) image of XDCP0044 with overlaid the soft ($[0.5 - 2]keV$, cyan) band Xray Chandra contours. Red circles indicate the 5 point-like sources (AGN) identified by Tozzi *et al.* (2015) within $30''$ ($250kpc$) from the cluster center.

In this work, we focused on a very small region ($70kpc \times 70kpc$) of the cluster core (right panel of Fig. 1) for which a detailed multiwavelength study has been conducted by combining the information derived from X-ray to optical, near-infrared (NIR) and radio bands, both photometrically and spectroscopilly (see Travascio *et al.* 2020 for more details).

2. Results

As visible in the right panel of Fig. 1, the core of XDCP0044, a very small region of 70kpc $\times$70kpc (slightly more than twice the milky way in size), appears very crowded. Through a SExtractor analysis (Bertin & Arnouts 1996), we indeed distinguished 16 photometric sources (green crosses in Fig. 1, right panel) and thanks to the spectroscopic SINFONI and KMOS data, we confirmed that at least seven of them are cluster members (magenta squares in Fig. 1, right panel), with redshifts ranging from $z = 1.5567$ to $z = 1.5904$ ($\Delta z \simeq 0.0337$), consistently with the redshift of the cluster. As visible in Fig. 1,

https://doi.org/10.1017/S1743921320003105 Published online by Cambridge University Press

these sources appear quite blue (the SFR of the entire region is $\sim 500 M_\odot/yr$, Santos *et al.* 2015) with disturbed morphology, and seems to be clustered in two galaxy complexes:

• **Complex A**, in the top-left corner of the central region of XDCP0044, includes at least 4 galaxies within 20 kpc in projected distance. It was detected in the HAWK-I image by Fassbender *et al.* (2014) as a single source and identified as the BCG, although with several extensions, interpreted as sign of ongoing or recent mergers.

• **Complex B**, located at the center of the analyzed field, is made of two sources at $d_{proj} \sim 5kpc$. One of the sources is an X-ray AGN discovered by Tozzi *et al.* (2013)

The two complexes are very close to each other, i.e. $d_{proj} \sim 35kpc$.

2.1. *AGN and SF activity*

Interestingly, in two of the analyzed sources, `a2` at the center of Complex A and `b1` in Complex B, the Hα emission line is broad (FWHM$>$1500 km/s), indicating galaxies with active nuclei (AGN). Moreover, the analysis of the line ratios ([NII]/Hα vs [OIII]/Hβ) in the BPT diagram for `a3` (the only source with all four lines measured), showed that `a3` is indeed an AGN. Three AGN have been thus discovered in the central (very small, i.e. $\sim 70kpc \times 70kpc$) region of the cluster (red and blue stars in the right panel of Fig. 1). Source `b1`, at the center of Complex B, is an X-ray point like source. From the analysis of its Chandra X-ray spectrum, we found that it is a luminous ($L_{[2-10keV]} \sim 10^{44} erg/s$) and moderately obscured ($log(N_H/cm^2) = 22.7$) AGN. From the broad (FWHM$\sim$2200 km/s) Hα line, we estimated its BH mass using the virial formula by Greene & Ho (2005), finding $M_{BH} = 7.2 \times 10^7 M_\odot$. Moreover, the bolometric luminosity has been computed by applying the bolometric correction by Runnoe *et al.* (2012) to the 5100Å luminosity, estimated from the linear interpolation of the F105W and F140W HST magnitudes. Combining the derived parameters, we found that `b1` is accreting at a high rate, i.e. $\lambda_{Edd} = 0.46$. Source `b1` has also been detected in ALMA continuum at 230 GHz which revealed cold dust emission from the host galaxy, detected at 5σ significance. Assuming different QSO SEDs and normalizying them at the observed ALMA flux, we derived a SFR in the range $[150 - 490] M_\odot/yr$, consistent with the SFR derived from Herschel for the entire central region ($452 \pm 58 M_\odot/yr$, Santos *et al.* 2015), suggesting that most of the IR emission, and therefore of the SF, might be associated to `b1`. No radio emission is associated to this source. Finally, we derived the stellar mass of its host galaxy assuming a constant M/L_K ratio (Madau *et al.* 1998) and a Chabrier (2003) initial mass function, finding $logM_\star \sim 11.8 M_\odot$.

Sources `a2` and `a3`, in the very crowded Complex A, have not been detected in the Chandra X-ray data. A 3σ upper limit on the X-ray luminosity has been derived to be of the order of $L_{[2-10keV]} < 10^{43} erg/s$, assuming an unabsorbed power-law with Γ=1.9. For `a2`, from the bolometric luminosity, as derived from $L_{5100\AA}$ (i.e. $log(L_{bol}/[erg/s]) \sim 45.4$), and by applying $k_{bol}[2 - 10keV] \sim 18.96$ (Duras *et al.* 2020), we expect an intrinsic luminosity $L_{[2-10keV]} \sim 10^{44} erg/s$. Such value is more than 1dex higher compared to the derived X-ray luminosity upper limit, thus suggesting a high level of X-ray obscuration ($log(N_H/cm^2) > 23.8$). From the broad ($FWHM \sim 1900 km/s$) $H\alpha$ line, we estimated that the BH of `a2` has a mass of $M_{BH} = 3.2 \times 10^7 M_\odot$, and accretes at $\lambda_{Edd} \sim 0.51$. While no emission has been found in ALMA corresponding to `a2`, JVLA 1.5 GHz extended radio emission has been detected spatially correlated to it. Under the assumption that such radio signal is produced by a single source, its power (logP[1.5 GHz] = 23.45) would suggest a likely (60 to 80% of probability) AGN powered radio emission, according to the relation introduced by Magliocchetti *et al.* (2014, 2018). However, there is a not negligible probability that such emission is on the contrary due to SF processes. In this case the measured radio luminosity would translate into a $SFR \sim 100\ M_\odot/yr$ according

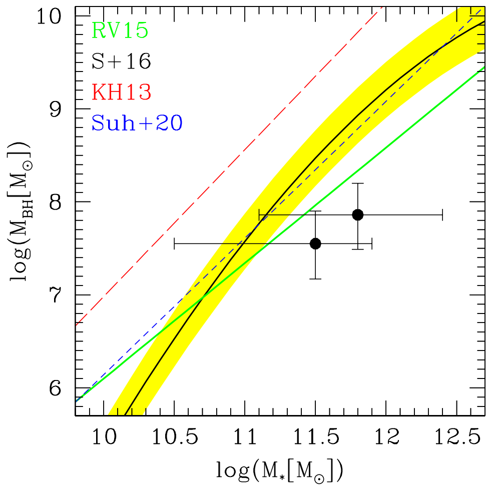

Figure 2. Correlations between central black hole mass and host galaxy total stellar mass for the two broad line AGN discovered in the core of XDCP004 (black circles with errors). As reference, the dashed red line is a linear fit to the sample of Kormendy & Ho (2013, KH13) by Shankar *et al.* (2019), while the solid green line is the fit to local AGN by Reines & Volonteri (2015, RV15) and the short-dashed blu line is the fit by Suh *et al.* (2020) to local + high-z AGN. Finally the solid black line is the de-biased $M_{BH} - M_{\star}$ relation derived by Shankar *et al.* (2016, S+16) with its scatter (yellow area).

to the relation by Brown *et al.* (2017). Finally, as for `b1`, we derived the stellar mass of its host galaxy, finding $log M_{\star} \sim 11.5 M_{\odot}$.

Summarizing, in the core of XDCP0044 we discovered three AGN hosted in massive and star-forming galaxies, i.e. two luminous, highly accreting and obscured/moderately obscured type-1 AGN and one X-ray and optically obscured type-2 AGN.

2.2. *The $M_{BH} - M_{\star}$ plane*

We studied the location of the two discovered type-1 AGN with broad Hα in the $M_{BH} - M_{\star}$ plane (Fig. 2). Both of them lie below the Kormendy & Ho (2013) relation for local inactive galaxies with $\Delta log(M_{BH}/M_{\star})$, computed perpendicular to the local relation, at $\sim 2\sigma$ from it. Their location is more consistent, within the large errors, with the more recent determination of the local scaling relation for active galaxies at $z < 0.055$ computed by Reines & Volonteri (2015) (green line in Fig. 2). Moreover, our data points lie close to the fit recently found by Suh *et al.* (2020) by including local plus high-z (up to z=2.5) AGN and to the unbiased $M_{BH} - M_{\star}$ relation computed by Shankar *et al.* (2016), who interpreted the discrepancy between the observed location of quiescient and active galaxies in the $M_{BH} - M_{\star}$ plane as an observational bias (Shankar *et al.* 2019). Indeed, our newly discovered $z \sim 1.6$ AGN have $M_{BH}/M_{\star}$ ratio consistent with local active galaxies, thus showing no or negligible evolution in the intrinsic $M_{BH} - M_{\star}$ relation, in agreement with most recent works (Shankar *et al.* 2019; Suh *et al.* 2020).

3. Conclusions

XDCP0044, a massive galaxy cluster at $z \sim 1.6$, allowed us to study the processes responsible for the BCG formation in the epoch when both SF and nuclear activity are at their peak (Madau & Dickinson 2014). We confirm that high-z galaxy cluster cores show different properties compared to the z=0 ones. Indeed, no single, early-type BCG has been detected in the core of XDCP0044, which is found to host a large number (at least 7 confirmed) of highly star-forming interacting galaxies, grouped in two main merging systems, both hosting also AGN activity. These three AGN provide one of the closest AGN triple at $z > 1$ revealed so far with a minimum (maximum) projected distance of 10 kpc (40 kpc) and their proximity implies a future merger between them.

These results lead to a scenario in which the AGN activity is triggered during the formation of the cluster BCG, when mergers between gas-rich galaxies provide the fuel for the AGN and for triggering starburst activity in galactic nuclei. Assuming that the 7 confirmed cluster members will merge to form the local BCG, we find that in a time scale of a couple of Gyrs, all galaxies in the core of XDCP0044 will experience several major mergers, forming a massive central galaxy with a final stellar mass of $1.0 \times 10^{12} M_{\odot}$ at $z \sim 1$, in agreement with what predicted by semi-analytic models (De Lucia & Blaizot 2007). In fact, we considered the case in which Complex A and B are clusters sub-clumps, each of which will aggregate to form a cD-like galaxy through a gravitational phase transition and then move towards the X-ray centroid in a dynamical friction time to finally merge to form the final BCG. According to this scenario, all these galaxies will merge in ∼2.5 Gyrs.

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https://doi.org/10.1017/S1743921320003105 Published online by Cambridge University Press