

X-ray cool core remnants heated by strong radio AGN feedback

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ABSTRACT

Strong AGN heating provides an alternative means for the disruption of cluster cool cores (CCs) to cluster mergers. In this work, we present a systematic *Chandra* study of a sample of 108 nearby ($z < 0.1$) galaxy clusters, to investigate the effect of AGN heating on CCs. About 40 per cent of clusters with small offsets between the BCG and the X-ray centre (≤ 50 kpc) have small CCs. For comparison, 14 of 17 clusters with large offsets have small CCs, which suggests that mergers or sloshing can be efficient in reducing the CC size. Relaxed, small CC clusters generally have weak radio AGNs ($P_{1.4\text{GHz}} < 10^{23}$ W Hz⁻¹), and they show a lack of systems hosting a radio AGN with intermediate radio power ($2 \times 10^{23} < P_{1.4\text{GHz}} < 2 \times 10^{24}$ W Hz⁻¹). We found that the strongest circumnuclear (< 1 kpc) X-ray emission only exists in clusters with strong radio AGN. The duty cycle of relaxed, small CC clusters is less than half of that for large CC clusters. It suggests that the radio activity of BCGs is affected by the properties of the surrounding gas beyond the central ~ 10 kpc, and strong radio AGNs in small X-ray CCs fade more rapidly than those embedded in large X-ray CCs. A scenario is also presented for the transition of large CCs and coronae due to radio AGN feedback. We also present a detailed analysis of galaxy cluster 3C 129.1 as an example of a CC remnant possibly disrupted by radio AGN.

Key words: galaxies: clusters: individual: 3C 129.1 – galaxies: jets – X-rays: galaxies: clusters.

1 INTRODUCTION

As the most massive virialized structure in the Universe, clusters of galaxies are excellent laboratories to study physical processes in structure formation. Galaxy clusters are permeated with the hot, X-ray emitting intracluster medium (ICM). When the radiative cooling time of the hot gas is shorter than the age of the system, in the absence of heating, the hot gas cools, condenses, and flows towards the centre (e.g. Fabian 1994). However, much less cool gas has been found by *Chandra* and *XMM-Newton* than the prediction from the cooling flow models (e.g. David et al. 2001; Peterson et al. 2001), suggesting there is a heating source compensating for the radiative cooling. Now, feedback from the central active galactic nuclei (AGNs) appears to be the most promising heating source among many possibilities, and it has been widely accepted that AGN feedback plays an important role in galaxy formation and evolution (e.g. McNamara & Nulsen

2007; Fabian 2012; Gaspari, Tombesi & Cappi 2020; Eckert et al. 2021; Donahue & Voit 2022; Hlavacek-Larrondo, Li & Churazov 2022; Heckman & Best 2023).

AGN outflows may simultaneously explain the quenching of star formation in massive galaxies, the exponential cut-off at the bright end of the galaxy luminosity function, the supermassive black hole mass-bulge mass relation, and the quenching of cooling-flows in cluster cores (e.g. Begelman & Nath 2005; Scannapieco, Silk & Bouwens 2005; Croton et al. 2006). Outflows from radio AGN are especially important locally because nearly all bright radio galaxies are hosted by early-type galaxies that dominate the high end of the luminosity function and the galaxy population in clusters. Radio-loud AGNs favour dense environments and many are found in galaxy groups and clusters, embedded in the X-ray emitting intracluster medium (ICM) and intragroup medium (IGM) (e.g. Best et al. 2005). In the nearby Universe, a radio-loud AGN, usually hosted by the brightest cluster galaxy (BCG) of a cluster or a group, can drive energetic radio jets, which extend outwards, inflate radio lobes, and create cavities and/or shocks visible in X-ray images (e.g. Churazov

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et al. 2001). The great mechanical power of radio AGN cannot only quench cooling in cluster cool cores, but also drive the ICM properties away from those defined by simple self-similar relations involving only gravity (e.g. McNamara & Nulsen 2007; Sun 2012).

With the help of the superior angular resolution of *Chandra*, the relation between radio AGN and X-ray cool cores has been established. Cluster cores seem to be bimodal in the core entropy distribution, which is naturally connected with cool core (CC) and non-cool core (NCC) clusters, respectively (e.g. Cavagnolo et al. 2009). This CC/NCC classification can also be determined using central cooling time, central temperature gradient, central density, surface brightness cuspliness, and central entropy (e.g. Leccardi & Molendi 2008; Hudson et al. 2010; McDonald et al. 2013, 2017; Ghirardini et al. 2019). However, intermediate objects may be classified differently using different diagnostic methods. While radio AGNs are typically enhanced in CC clusters, many radio AGNs are present in NCC clusters. Sun (2009) showed that the traditional CC/NCC dichotomy is too simple and the CCs hosting BCG with a strong radio AGN ($P_{1.4\text{GHz}} > 2 \times 10^{23} \text{ W Hz}^{-1}$) can be divided into two classes: the large cool core (LCC) class and the corona class based on the 0.5–2.0 keV luminosity within the cool core. Small coronae, which can be misidentified as X-ray AGNs at $z > 0.1$, are mini-cool cores in groups and clusters. Thus, the distinction between CCs and NCCs is more complicated, as some NCC clusters actually have small coronae in their centres. The corona fraction is at least comparable with that of LCCs for clusters hosting BCGs with strong radio AGNs in the Sun (2009) sample and some coronae may be the remnants of LCC (e.g. Sun 2009).

The CC/NCC distribution is assumed to result from different evolutionary histories of galaxy clusters, but the origin of this distribution is not well understood. The transition between CC clusters and NCC clusters is important to understand the formation and evolution of cluster CCs (see Burns et al. 2008). A joint analysis of *Chandra* X-ray and South Pole Telescope Sunyaev-Zel'dovich observations found that the CC fraction in a sample of clusters at $0.3 < z < 1.3$ is remarkably stable although the mass of clusters has increased by a factor of ~ 4 over the past 9 Gyr (Ruppin et al. 2021). This suggests that the CC disruption is balanced well by CC restoration (e.g. a NCC cluster relaxes to the CC state) since high redshift (McDonald et al. 2017). Using a multitemperature spectral analysis, Molendi et al. (2023) found that there may exist a small amount of low entropy gas with short cooling times in the subclass of NCC clusters known as CC remnant systems, therefore allowing a transformation to CC systems on a relatively short time-scale. One of the main mechanisms to transform CC to NCC clusters is cluster mergers. Using a well-defined X-ray selected cluster sample, Rossetti et al. (2011) found that none of the dynamically disturbed systems, often showing large-scale radio haloes, can be classified as a CC (e.g. Cassano et al. 2013; Cuciti et al. 2015). Simulations suggest that CCs can only be destroyed by high-energy, low angular momentum major mergers (e.g. Hahn et al. 2017). A recent study of galaxy cluster A1763 shows that large-scale gas-sloshing could also disrupt cluster CCs and establish NCC (Douglass et al. 2018). However, the physics related to core restoration and destruction is very difficult to capture in simulations.

The alternative mechanism for CC disruption is by powerful outbursts from the central AGN through the cold AGN feedback mechanism. That is, the hot gas in the cores of galaxy groups/clusters cools to form a multiphase medium consisting of cold clouds that fall inward and feed the supermassive black hole (SMBH). The accretion rate can be boosted by orders of magnitude via a process known as chaotic cold accretion (CCA)/cold gas precipitation (e.g. Pizzolato &

Soker 2005; Sharma et al. 2012; Gaspari, Ruszkowski & Oh 2013; Voit & Donahue 2015; Voit 2019; Qiu et al. 2021; McKinley et al. 2022; Wittor & Gaspari 2023). The large amount of energy released by an energetic AGN outburst can disrupt the CCs and leave CC remnants. They may be more common in groups, where CCs are smaller than those in clusters. The impact of AGN outbursts is much more pronounced in low-mass systems due to their shallow gravitational potential (e.g. Giodini et al. 2010; Sun 2012). X-ray cavities have been detected in only a few galaxy groups hosting radio luminous AGNs ($P_{1.4\text{GHz}} > 10^{24} \text{ W Hz}^{-1}$), e.g. NGC 4782 (Machacek et al. 2007), NGC 4261 (O'Sullivan et al. 2017), PKS B2152-699 (Worrall et al. 2012), 3C 88 (Liu et al. 2019), IC 4296 (Grossová et al. 2019). Fewer cases of X-ray cavities have been reported in groups than in clusters due to the relatively low X-ray luminosity of the smaller X-ray atmospheres that enclose the lobes of luminous radio AGN in groups. In another way, CCs could have been disrupted by AGN outbursts and turned into coronae in galaxy groups (e.g. Sun 2009; O'Sullivan et al. 2010). CC remnants also exist in galaxy clusters. Rossetti & Molendi (2010) studied the cores of a sample of 35 clusters with XMM-*Newton* data and selected 12 CC remnants based on the excess metal abundances near the cluster centres. These systems generally have rather dense cores and most of them may be classified as weak CCs (e.g. Hudson et al. 2010). One of them (A3558) also hosts a luminous, small corona.

While the CCs in galaxy groups can be more easily disrupted by AGN outburst, in this paper, we aim to use a sample of nearby hot galaxy clusters to study how transitions between the states of cluster cores are related to radio AGN feedback. The paper is organized as follows. The cluster sample selection is defined in Section 2. The data analysis is presented in Section 3. In Section 4 we present the results. After studying the general properties of the sample, we present a detailed analysis of the cluster 3C 129.1 with a CC remnant, associated with a strong radio AGN in Section 5. Discussions are in Section 6 and Section 7 contains the conclusions. Throughout the paper, we assume a cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$.

2 SAMPLE SELECTION

We want to examine the relationship between the radio AGN in the central BCGs and the transitions between X-ray LCCs and coronae of nearby hot galaxy clusters. The corona, typically with a low X-ray luminosity, can be easily missed at $z > 0.1$. In order to study the properties of cluster CCs, especially for clusters with small coronae, we need to resolve the properties of hot gas (e.g. temperature and density) to the very central region, e.g. within a few kpc. Therefore, we selected our sample from the Meta-Catalogue of X-ray detected Clusters of galaxies (MCXC; Piffaretti et al. 2011) based on the following criteria: (1) $z < 0.1$; (2) $kT_{\text{ICM}} > 3 \text{ keV}$ (The temperatures were obtained from the previous studies in the literature or from our own analysis). Here we chose a temperature cut of 3 keV since we focused on hot galaxy clusters instead of galaxy groups; (3) with *Chandra* observations (due to its unprecedented spatial resolution); (4) $> \sim 35$ net counts in the 0.5–3.0 keV band within the central 5 kpc in order to constrain the properties of the coronae if exist. The constraints on the CC properties depend on many factors, such as the *Chandra* exposure, the distance of cluster, the Galactic absorption and so on. Therefore, we first used this low threshold of 35 counts to include as many clusters as we could. We then examined the clusters case-by-case and excluded those clusters where we could not make statistical constraints on the CC properties. Finally, we have a total of 108 galaxy clusters in our sample.

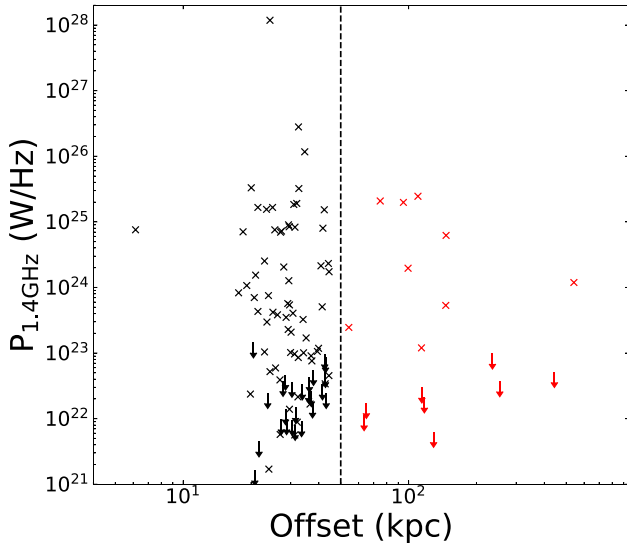


Figure 1. The radio luminosity of central BCGs at 1.4 GHz versus the offsets between the positions of the BCG and the X-ray cluster centre. Clusters with the offsets smaller than and greater than 50 kpc are on the left and right side of the vertical dash line, respectively.

Our main interest is to investigate the effect of radio AGN heating by the central BCGs on the CCs of galaxy clusters. However, some clusters in our sample show signatures of recent mergers, e.g. large offsets between the central BCG, the most luminous galaxy in the Two Micron All Sky Survey (2MASS) K_s band in a cluster, and the X-ray cluster centre. The X-ray centre for each cluster is determined with the SPA code¹ by computing the median photon location in an iteratively shrinking aperture, and this median centre can compromise between the X-ray peak and the cluster centroid (Mantz et al. 2015). In this study, we used the offset as the separation between the BCG and this median centre instead of the separation between the BCG and the X-ray peak. In Fig. 1, we plot the offsets between the central BCG (its position is obtained from 2MASS K -band image) and X-ray cluster centre versus the radio luminosities of the central BCGs at 1.4 GHz. There are 17 systems with offsets greater than 50 kpc (if we change the threshold to 60 kpc, the number of clusters with offsets greater than the threshold decrease only by one). The radio fluxes of the central BCGs are obtained from the NRAO VLA Sky Survey (NVSS) and the Faint Images of the Radio Sky at Twenty Centimeter (FIRST) survey. If neither of them is available, we used radio surveys in other bands, e.g. the Sydney University Molonglo Sky Survey (SUMSS) at 843 MHz, and converted to the flux at 1.4 GHz assuming a radio spectral index of $\alpha = 0.8$ (defined as $S \propto \nu^{-\alpha}$ where S is the radio flux and ν is the frequency). In our sample ~ 55 per cent of BCGs (59 out of 108) have $P_{1.4\text{GHz}} > 10^{23}$ W Hz^{-1} , and ~ 31 per cent of BCGs (34 out of 108) have $P_{1.4\text{GHz}} > 10^{24}$ W Hz^{-1} . In Table 1 we list the properties of our cluster sample.

3 DATA ANALYSIS

We performed the standard *Chandra* data analysis using CIAO 4.12 and CALDB version 4.9.0. For each observation, we reprocessed the data from level 1 event files using the CHANDRA_REPRO script to account for afterglow, bad pixels, charge transfer inefficiency, and

Table 1. Cluster sample properties.

$P_{1.4\text{GHz}}^a$ (W Hz^{-1})		Offset ^b (kpc)		$r_{4\text{Gyr}}^c$ (kpc)		
$>10^{23}$	$<10^{23}$	<50	>50	>15	<6	6–15
59	49	91	17	58	20	30

Note. *a*: radio luminosity of central BCG at 1.4 GHz; *b*: The offset between the BCG and the X-ray cluster centre. *c*: Cooling radius where the gas cooling time is 4 Gyr.

time-dependent gain correction. The improved background filtering was applied for observation taken in Very Faint (VFaint) mode by setting CHECK_VF_PHA as ‘yes’ to remove bad events that are likely associated with cosmic rays. We generated the light curve to remove any period affected by background flares. The point sources were detected in the 0.5–7.0 keV count images using the CIAO tool WAVDETECT and then removed from our data analysis. We used the CALDB blank sky background files in our data analysis. For each observation the standard blank sky file for each chip was reprojected to match the time-dependent aspect solution, and normalized to match the count rate in the 9.5–12.0 keV band to account for variations in the particle background. We estimated the X-ray sky background residuals using background models including two APEC components with zero redshift and Solar abundance and one power-law component. For clusters with regions free of cluster emission, we extracted the spectrum from the region where the surface brightness is approximately constant. If cluster emission is full of the field of view, we extracted the spectra from two regions, one background-dominated outer region, and one source-dominated inner region. We fit two spectra simultaneously, with the normalizations of the background models linked (e.g. Sun et al. 2009). The best-fitting background residual models were then used in spectral and surface brightness analysis. In fact, the variations of X-ray background have little impact on our results since our study is focused on the bright X-ray cool cores. For the spectral fitting, we used XSPEC version 12.10.0 and ATOMDB 3.0.9 with the solar abundance table of Asplund et al. (2009). The absorption model is TBABS.

3.1 Cool core size and luminosity

In this study, we aim to study the properties of cluster CCs, and the transitions between the large CCs and small CCs due to the radio AGN feedback. For this purpose, we need to define the sizes of CCs and estimate their X-ray luminosities.

X-ray CCs of galaxy clusters are usually defined based on the cooling time of the gas. We used a cooling radius of $r_{4\text{Gyr}}$, where the gas cooling time is 4 Gyr instead of the conventionally used value of 7.7 Gyr, to quantify the size of CCs. Previous study has shown that $r_{4\text{Gyr}}$ can effectively represent the whole region for small coronae (Sun et al. 2007), and further reasons to choose this radius were discussed in Sun (2009). In this work, we adopted this cooling radius to distinguish between the LCCs and small coronae. A cooling radius with a somewhat different cooling time, e.g. 3–5 Gyr, does not alter our main conclusions.

To derive the cooling time profiles toward the centres of clusters, we generally followed the method used in Cavagnolo et al. (2009) to obtain the gas temperature and density profiles. First, we extracted the spectra in a series of annuli within the central ~ 100 kpc centred on the BCG and explored the properties of the hot gas as close to the centre as possible. We then obtained the gas temperature and abundance profiles by fitting an absorbed thermal model to the spectra, with the

¹<https://sites.google.com/site/adambmantz/work/morph14>

fixed background models scaled to the extraction area. Secondly, we extracted the surface brightness profiles in the 0.5–7.0 keV band using concentric annular bins centred on the BCG. We deprojected the surface brightness profiles using the ‘onion-peeling’ method to obtain the gas density profile (e.g. Kriss, Cioffi & Canizares 1983; Cavagnolo et al. 2009), taking into account the variations of temperature and metal abundance. We checked if the surface brightness profiles in the soft band (e.g. 0.5–2.0 keV) are used, the derived density profiles are consistent with the results obtained using the surface brightness in the 0.5–7.0 keV band. Once we had the temperature and density profiles, we calculated the cooling time profiles using equation $t_{\text{cool}} = \frac{3nkT}{2n_e n_H \Lambda(T, Z)}$, where n is the total number density, n_e and n_H are the electron and proton densities, $\Lambda(T, Z)$ is the cooling function for a given temperature and metal abundance. Finally we calculated the cooling radius $r_{4\text{Gyr}}$ based on the cooling time profile. In our sample, we defined X-ray CCs as LCCs if $r_{4\text{Gyr}} > 15$ kpc, and small CCs if $r_{4\text{Gyr}} \leq 15$ kpc (corona class with $r_{4\text{Gyr}} \leq 6$ kpc and transition CCs if $6 < r_{4\text{Gyr}} \leq 15$ kpc).

Many clusters in our sample were studied by Cavagnolo et al. (2009) in detail. They provided entropy profiles that can be used to distinguish CC and NCC clusters, as well as the cooling time profiles, which can be used to calculate the cooling radius $r_{4\text{Gyr}}$. However, we noticed that the radial profiles were centred on the ICM X-ray peak in Cavagnolo et al. (2009), while ours were centred on the BCG. Therefore, we used the cooling time profiles in Cavagnolo et al. (2009) if the offsets between the BCGs and the cluster centres used in their studies are smaller than ~ 5 kpc or ~ 2 kpc for clusters with LCCs or small CCs, respectively. In Tables 2, 3, and 4, we indicated which cluster was from our data analysis and for which cluster we used their results.

For corona systems, there is usually an enhancement of the surface brightness in the centre (e.g. Sun et al. 2007). In our study, if the derived cooling radius $r_{4\text{Gyr}}$ is less than 6 kpc and the surface brightness of the system is flat in the centre, we took the cooling radius to be the upper limit for the corona size. Some clusters do not have either a large CC or a central corona, e.g. A2147 (Sun et al. 2007). The central cooling time of these clusters is much larger than 4 Gyr, and they show no central enhancement of X-ray surface brightness. The previous studies have shown that the X-ray coronae of galaxies in galaxy clusters are quite compact with an extension of a few kpc, and can extend to ~ 10 kpc in some cases (e.g. Sun et al. 2007). Here we used 3 kpc as an upper limit of the CC size for these galaxy clusters.

Once the CC size was derived, we were able to measure the cooling luminosity. We extracted the spectrum from the cool core region centred on the BCG within the radius of $r_{4\text{Gyr}}$. The background spectrum was extracted within the region from $r_{4\text{Gyr}}$ to $2r_{4\text{Gyr}}$. We then fitted the spectrum with an absorbed thermal component for the thermal gas, and a power-law component to account for any possible emission from the central AGN. Unlike in large CC systems, the gas abundance in small CC systems usually cannot be constrained, so we fixed it at 0.8 Solar, a typical value found in corona systems (e.g. Sun et al. 2007). For some clusters (e.g. NCC cluster A2147), the extracted spectrum has very limited counts, so we also fixed the temperature of the thermal component to 0.7 keV in order to derive an upper limit for the luminosity, as in Sun et al. (2007). We measured the bolometric luminosity within the CC in our study. The properties of each cluster in our sample are summarized in Table 2 for clusters with small offsets and large CCs, Table 3 for clusters with small offsets and small CCs, and Table 4 for clusters with large offsets.

4 RESULTS

4.1 Cool core size versus radio luminosity

We plotted the cool core size versus radio luminosity of the central BCG at 1.4 GHz in Fig. 2. The clusters with transition CCs are shown in the shaded region, while corona clusters and LCC clusters are on the left and right, respectively. The top panel of Fig. 2 shows the CC size distributions for galaxy clusters with small and large offsets, respectively, from the Gaussian kernel density estimates (KDEs). We looked at the systems with small offsets (≤ 50 kpc) between the central BCG and the X-ray cluster centre, and about 40 per cent of them (36 out of 91) have small CCs. While for the systems with large offsets (> 50 kpc), we found most of them have small CCs, i.e. only 3 out of 17 clusters have large CCs, and the largest cooling radius is ~ 29 kpc (A2440). This comparison of two subsamples with different offsets suggests that cluster mergers or sloshing can disrupt LCCs efficiently to reduce the cool core size. Mergers trigger bulk motion or sloshing of cool cores that spreads the metal-rich gas in a larger volume.

We checked the relation between the CC size and radio luminosity of the BCG for clusters with small offsets. There is a weak correlation between the CC size and radio power for clusters with large CCs, with a correlation coefficient of 0.29 ± 0.12 obtained using the tool LINMIX.² While there is no correlation between them for clusters with small CCs, with a correlation coefficient consistent with zero.

We also showed the radio power distributions for the relaxed and disturbed systems in the right panel of Fig. 2. We found that the fraction of radio weak systems (~ 47 per cent with $P_{1.4\text{GHz}} < 10^{23}$ W Hz⁻¹) in disturbed clusters is comparable to that (45 per cent) in relaxed clusters, though the total number of disturbed clusters is much smaller in our sample. For clusters with small offsets, we plotted the radio power KDEs for small CCs and large CCs, respectively. The large CC systems show a relatively continuous distribution of radio power. However, most of small CC systems (71 per cent) have a weak radio AGN with radio power $P_{1.4\text{GHz}} < 10^{23}$ W Hz⁻¹ and there is a lack of small CC systems with intermediate radio power from $\sim 2 \times 10^{23}$ to $\sim 2 \times 10^{24}$ W Hz⁻¹. By contrast, 19 large CC clusters fall within this radio power range. For systems with strong radio AGNs, there is a total of 10 small CC clusters, while there are 40 large CC clusters. This may suggest different duty cycles (defined as the fraction of the time when the galaxy hosts a radio-loud AGN, see more details on Section 6.2) of radio AGN feedback processes in large CC and small CC clusters. In large CCs, the radio AGN stage is more continuous. In small CCs, the radio AGNs spent a much shorter time in the radio strong stage than in the radio weak stage.

4.2 Cool core luminosity versus radio luminosity

We then examined BCGs in the plane of the bolometric X-ray luminosity within the cooling radius $r_{4\text{Gyr}}$ versus radio luminosity at 1.4 GHz in Fig. 3. As shown in Fig. 3 we divided all CCs into two classes, small CCs and large CCs with a dividing bolometric X-ray luminosity of 10^{42} erg s⁻¹. This is relatively consistent with the previous study, where they used a dividing CC luminosity of 4×10^{41} erg s⁻¹ in 0.5–2.0 keV band (Sun et al. 2009), considering that the conversion factor from 0.5–2 keV luminosity to bolometric luminosity for low-temperature corona gas is ~ 2 . In this way, the division of large CCs and small CCs based on the cool core luminosity

²<https://github.com/jmeyers314/linmix>

Table 2. Summary of results for clusters with small offsets (≤ 50 kpc) and large cool cores ($r_{4\text{Gyr}} > 15$ kpc).

Cluster	z^a	$P_{1.4\text{GHz}}^b$ $\log(P_{1.4\text{GHz}}/W \text{ Hz}^{-1})$	Offset ^c (kpc)	$r_{4\text{Gyr}}^d$ (kpc)	$L_{X,\text{bol}}^e$ ($10^{44} \text{ erg s}^{-1}$)	Note ^f
2A0335+096	0.0346	23.0	23.0	78.0 ± 0.7	1.42 ± 0.03	0
A85	0.0557	23.6	30.7	56.6 ± 1.7	$1.04_{-0.08}^{+0.01}$	1
A133	0.0569	24.8	18.4	52.4 ± 1.8	$0.37_{-0.04}^{+0.03}$	1
A426	0.0176	25.2	24.9	82.9 ± 2.3	$4.00_{-0.20}^{+0.10}$	1
A478	0.0860	23.8	20.7	92.8 ± 5.6	$7.65_{-0.16}^{+0.03}$	1
A496	0.0328	23.5	23.5	55.5 ± 5.8	0.63 ± 0.02	1
A780	0.0549	26.4	32.5	59.7 ± 1.3	1.14 ± 0.05	1
A1644	0.0475	23.7	41.4	27.0 ± 1.9	0.053 ± 0.004	1
A1650	0.0846	<22.6	36.3	43.5 ± 5.6	$0.46_{-0.03}^{+0.01}$	1
A1651	0.0853	23.0	39.4	24.4 ± 11.8	0.083 ± 0.012	0
A1668	0.0635	23.9	23.9	49.8 ± 3.1	$0.25_{-0.09}^{+0.10}$	0
A1775	0.0757	23.5	34.0	39.8 ± 1.0	0.087 ± 0.006	0
A1795	0.0633	24.9	29.6	80.5 ± 1.7	$3.16_{-0.14}^{+0.13}$	0
A2029	0.0779	24.9	6.2	79.9 ± 4.0	$4.59_{-0.17}^{+0.15}$	1
A2033	0.0809	24.9	29.3	25.5 ± 5.7	0.061 ± 0.006	0
A2052	0.0345	25.2	23.4	44.8 ± 0.6	$0.30_{-0.02}^{+0.01}$	1
A2063	0.0341	22.6	26.9	35.8 ± 2.2	$0.075_{-0.025}^{+0.019}$	0
A2065	0.0729	23.1	39.9	32.4 ± 2.6	$0.11_{-0.04}^{+0.01}$	0
A2110	0.0971	23.3	30.1	55.5 ± 7.8	$0.47_{-0.04}^{+0.02}$	0
A2142	0.0904	<22.7	42.8	75.1 ± 4.7	2.67 ± 0.03	0
A2199	0.0310	24.9	25.5	51.2 ± 2.3	0.63 ± 0.01	1
A2244	0.0993	22.9	37.2	38.8 ± 2.3	0.38 ± 0.02	1
A2312	0.0944	24.2	44.4	21.9 ± 2.9	0.026 ± 0.004	0
A2457	0.0567	22.2	36.5	21.9 ± 6.3	$0.025_{-0.008}^{+0.002}$	0
A2495	0.0800	23.4	29.2	46.5 ± 6.2	0.39 ± 0.02	0
A2556	0.0883	<22.7	28.4	64.4 ± 5.1	0.86 ± 0.03	1
A2566	0.0824	23.6	21.5	76.4 ± 3.0	0.54 ± 0.06	0
A2589	0.0411	<22.0	28.8	20.8 ± 6.4	0.025 ± 0.001	1
A2597	0.0830	25.5	20.1	94.6 ± 9.2	3.01 ± 0.03	1
A2626	0.0546	23.6	26.2	39.4 ± 2.4	0.19 ± 0.01	1
A2665	0.0564	23.6	25.0	31.0 ± 5.9	$0.12_{-0.02}^{+0.01}$	0
A3112	0.0761	25.2	21.5	56.8 ± 3.2	1.74 ± 0.03	1
A3526	0.0099	24.0	19.1	40.5 ± 0.5	0.081 ± 0.007	1
A3528S	0.0574	24.8	27.1	27.7 ± 5.3	0.12 ± 0.01	1
A3528N	0.0541	24.4	23.0	30.3 ± 9.1	$0.11_{-0.03}^{+0.01}$	0
A3571	0.0386	22.1	29.6	22.3 ± 3.8	0.072 ± 0.005	1
A3809	0.0626	<22.6	27.7	45.8 ± 3.6	0.13 ± 0.04	0
A4038	0.0288	22.7	24.3	50.9 ± 1.2	$0.17_{-0.02}^{+0.01}$	0
A4059	0.0490	24.9	27.3	33.3 ± 1.4	0.090 ± 0.015	1
AWM7	0.0173	<21.2	20.8	25.8 ± 1.9	0.046 ± 0.002	1
BVH2007-81	0.0635	23.0	31.2	18.4 ± 8.4	0.027 ± 0.007	0
CYGNUSA	0.0561	28.1	24.3	58.8 ± 1.5	1.84 ± 0.02	1
MKW03S	0.0453	23.7	29.6	47.6 ± 4.4	0.42 ± 0.01	1
Ophiuchus	0.0285	22.8	25.7	36.0 ± 2.9	0.57 ± 0.02	1
RXCJ0649.3+1801	0.0639	<22.4	23.7	55.2 ± 9.6	0.18 ± 0.04	0
RXCJ1040.7-7047	0.0596	23.5	28.6	19.6 ± 7.2	0.018 ± 0.002	0
RXCJ1324.7-5736	0.0186	24.2	21.0	39.5 ± 2.2	0.11 ± 0.01	0
RXCJ1539.5-8335	0.0757	23.8	29.1	69.5 ± 3.8	1.73 ± 0.05	1
RXCJ1558.3-1410	0.0974	25.3	31.0	86.1 ± 1.3	1.52 ± 0.23	0
RXCJ1857.6+3800	0.0538	24.3	27.9	15.3 ± 2.5	$0.015_{-0.006}^{+0.002}$	0
RXJ1844.0+4532	0.0920	26.1	34.6	19.4 ± 1.2	0.048 ± 0.012	1
RXCJ2218.0-6511	0.0940	<23.1	20.5	32.4 ± 5.5	$0.15_{-0.04}^{+0.01}$	0
ZWCL0040.8+2404	0.0830	23.9	17.6	73.6 ± 2.2	1.08 ± 0.13	0
ZWCL1742.1+3306	0.0757	24.1	29.4	50.7 ± 7.5	$0.78_{-0.08}^{+0.04}$	1

Note. *a*: redshift of the central BCG; *b*: radio luminosity of the central BCG at 1.4 GHz; *c*: the offset between the cluster centre and the position of the central BCG; *d*: cooling radius with cooling time corresponding to 4 Gyr; *e*: X-ray bolometric luminosity within the cooling radius. *f*: Note '1' represents that $r_{4\text{Gyr}}$ is calculated based on the cooling time profiles in Cavagnolo et al. (2009) and '0' represents that $r_{4\text{Gyr}}$ is calculated from our analysis.

Table 3. Same as Table 2 but for clusters with small offsets (≤ 50 kpc) and small cool cores.

Cluster	z	$P_{1.4\text{GHz}}$ $\log(P_{1.4\text{GHz}}/W \text{ Hz}^{-1})$	offset (kpc)	$r_{4\text{Gyr}}$ (kpc)	$L_{X, \text{bol}}$ ($10^{41} \text{ erg s}^{-1}$)	Note
3C 129.1	0.0222	24.3	40.9	8.3 ± 1.1	$2.92^{+1.00}_{-0.95}$	0
A193	0.0474	23.2	35.1	7.6 ± 2.3	$1.70^{+0.33}_{-0.32}$	0
A376 ^a	0.0485	<22.1	28.5	15.9 ± 2.9	$5.18^{+4.22}_{-2.42}$	0
A401	0.0714	<22.5	41.5	<3.0	<0.10	0
A539	0.0291	<21.6	21.7	13.0 ± 2.1	$6.98^{+0.50}_{-0.94}$	1
A548E	0.0396	<22.0	33.5	14.9 ± 2.2	$8.23^{+1.19}_{-1.84}$	0
A576	0.0411	21.8	26.9	<3.0	<0.93	0
A644	0.0705	<22.5	36.0	<3.6	<0.33	0
A1060	0.0128	22.4	19.9	9.8 ± 3.7	0.33 ± 0.09	1
A1314	0.0336	22.9	32.4	6.1 ± 1.3	1.60 ± 0.14	0
A2107 ^b	0.0418	<22.0	27.3	13.8 ± 0.5	21.5 ± 0.9	1
A2124	0.0661	<22.4	37.0	<3.0	<0.12	0
A2147	0.0354	22.6	44.3	<3.0	<0.05	0
A2319	0.0546	<22.2	37.5	<3.0	<0.06	0
A2572	0.0392	23.0	30.0	6.8 ± 3.3	$2.55^{+1.84}_{-1.33}$	0
A2634	0.0305	24.4	44.1	7.2 ± 1.9	$3.59^{+0.25}_{-0.24}$	0
A2657	0.0402	<22.0	30.5	14.1 ± 3.5	$5.58^{+1.21}_{-2.53}$	1
A2670 ^b	0.0777	22.9	37.0	13.3 ± 4.6	$10.9^{+1.4}_{-2.1}$	0
A2734	0.0619	23.0	34.2	10.4 ± 2.9	$7.11^{+4.51}_{-2.75}$	0
A2877	0.0243	21.2	24.0	7.7 ± 1.1	8.11 ± 0.31	0
A3266	0.0602	<22.5	33.8	5.5 ± 1.4	$1.01^{+0.55}_{-0.47}$	1
A3330	0.0918	25.2	42.3	7.7 ± 2.8	$5.28^{+1.81}_{-2.27}$	0
A3341	0.0371	<21.9	31.4	12.1 ± 6.44	$5.22^{+1.18}_{-1.68}$	0
A3391	0.0551	25.5	32.6	3.3 ± 0.7	$2.35^{+0.39}_{-0.36}$	0
A3395S	0.0520	25.3	31.9	6.8 ± 1.4	$2.78^{+1.31}_{-0.96}$	0
A3532	0.0542	24.9	31.3	6.8 ± 4.6	$1.68^{+2.42}_{-0.93}$	0
A3558	0.0469	22.3	32.3	9.5 ± 3.5	$5.18^{+1.33}_{-1.26}$	1
A3560	0.0490	24.9	41.7	7.0 ± 1.9	$0.87^{+0.19}_{-0.18}$	0
A3827	0.0998	<23.0	42.5	9.9 ± 3.9	$0.77^{+0.66}_{-0.64}$	0
A3921	0.0938	<22.9	42.8	11.3 ± 2.6	$4.57^{+1.76}_{-1.79}$	0
MKW08	0.0274	21.8	31.3	7.2 ± 1.6	$2.39^{+0.31}_{-0.29}$	0
MS2216.0-0401	0.0942	<22.7	37.9	9.5 ± 1.6	$5.97^{+1.43}_{-1.38}$	0
RXCJ1614.1-6307	0.0616	<22.6	30.4	11.3 ± 2.7	$7.94^{+1.83}_{-1.54}$	0
SC1327-312	0.0501	<22.1	31.5	8.8 ± 2.9	$1.61^{+1.19}_{-0.77}$	1
SC1329-313	0.0439	21.9	32.1	5.9 ± 0.9	$0.64^{+0.18}_{-0.15}$	0
TrA Cluster	0.0494	<22.4	43.1	<3.0	<0.45	0
ZWCL1215	0.0750	22.5	42.7	6.7 ± 1.4	$1.95^{+0.80}_{-0.73}$	0

Note. *a*: $r_{4\text{Gyr}}$ is slightly larger than 15 kpc, while $L_{X, \text{bol}}$ is less than $10^{42} \text{ ergs s}^{-1}$. *b*: $r_{4\text{Gyr}}$ is less than 15 kpc, while $L_{X, \text{bol}}$ is larger than $10^{42} \text{ ergs s}^{-1}$.

is almost consistent with the division based on the CC size. We found three clusters in different classes with these two different criteria, A2107, A2670, and A376, with the former two having CC luminosities of $>10^{42} \text{ erg s}^{-1}$ while having CC sizes of <15 kpc, and the last one having a CC luminosity of $\sim 5 \times 10^{41} \text{ erg s}^{-1}$ while having a CC size of ~ 16 kpc. On the other hand, their exact classification has little impact on conclusions of our work.

In Fig. 3, the large CC clusters show a weak correlation between the CC luminosity and the radio luminosity of the BCG. More radio luminous sources generally reside in the larger cool cores, although with a large scatter. Using the tool LINMIX, we calculated a positive correlation coefficient of 0.38 ± 0.12 between the radio luminosity and CC luminosity of the large CC clusters. We also plotted the kinetic power based on the $P_{\text{radio}} - P_{\text{cavity}}$ relation from Bîrzan et al.

(2008) and Cavagnolo et al. (2009). For most of the large CC clusters, the inferred kinetic power exceeds the cooling luminosity. Notice that the cooling luminosity here is estimated within the cooling radius with the cooling time corresponding to 4 Gyr. Using a large cooling radius, e.g. with a typical cooling time of 7.7 Gyr, can have a higher cooling luminosity. In comparison, the small CC clusters do not show a correlation between the radio power and the CC luminosity, with a correlation coefficient consistent with zero. The radio luminous corona systems show that the inferred kinetic power could greatly exceed the CC luminosity, suggesting that most of the energy released from central AGN needs to be deposited outside of the corona in order for it to survive.

Radio and X-ray observations have shown that radio jets created by the central AGN can drill through the hot atmosphere of the

Table 4. Same as Table 2 but for clusters with large offsets (>50 kpc).

Cluster	z	$P_{1.4\text{GHz}}$ $\log(P_{1.4\text{GHz}}/\text{W Hz}^{-1})$	Offset (kpc)	$r_{4\text{Gyr}}$ (kpc)	$L_{X,\text{bol}}$ (10^{41} erg s^{-1})	Note
A13	0.0905	23.7	146	<3.0	<0.20	0
A119	0.0445	<22.0	63.5	2.7 ± 0.7	$0.16^{+0.11}_{-0.08}$	0
A754	0.0543	<22.2	65.0	<3.0	<0.10	0
A1142	0.0368	23.1	114	9.4 ± 2.1	1.26 ± 0.17	0
A1185	0.0347	<21.8	129	5.9 ± 2.3	$0.28^{+0.11}_{-0.09}$	0
A1367	0.0211	24.8	147	5.1 ± 1.7	0.80 ± 0.09	0
A1656	0.0239	23.4	54	4.1 ± 1.5	$0.78^{+0.15}_{-0.12}$	0
A2061	0.0791	<22.6	254	7.7 ± 1.0	$4.29^{+0.78}_{-0.79}$	0
A2256	0.0594	<22.3	117	<3.9	<0.50	0
A2384S	0.0956	24.1	541	24.4 ± 1.6	$22.8^{+3.6}_{-3.4}$	0
A2440	0.0902	<22.7	443	29.2 ± 3.8	$27.7^{+11.9}_{-9.2}$	0
A3376	0.0456	24.3	99	5.1 ± 1.6	$0.59^{+0.17}_{-0.14}$	0
A3627	0.0182	25.4	110	5.4 ± 0.3	4.42 ± 0.71	0
A3667	0.0557	<22.5	114	<3.6	<0.27	0
A3744	0.0384	25.3	95	6.1 ± 1.2	$0.75^{+0.31}_{-0.25}$	0
A4067	0.100	<23.0	235	28.2 ± 2.8	$47.4^{+17.6}_{-14.9}$	0
AS463	0.0399	25.3	75	7.9 ± 1.2	$1.66^{+0.31}_{-0.30}$	0

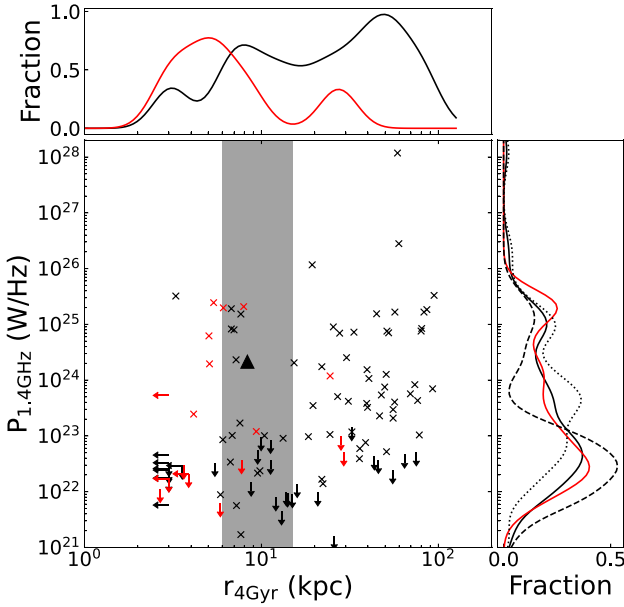


Figure 2. Cool core size versus radio power of the central BCG at 1.4 GHz. The shaded region shows the systems with cool core sizes between 6 and 15 kpc. On the left are systems with coronae and on the right are systems with large cool cores. Systems with small offsets are in black and those with large offsets are in red. The triangle symbol represents the cluster 3C 129.1 (see Section 5). The Gaussian KDEs for cool core size and radio power distributions of clusters with small offsets (black solid) and large offsets (red solid) are shown. The Gaussian KDEs for the radio power distribution for clusters with small offsets and with small cool cores ($r_{4\text{Gyr}} \leq 15$ kpc) and large cool cores ($r_{4\text{Gyr}} > 15$ kpc) are shown by the dashed line and the dotted line, respectively. For clarity purpose, we did not plot the error bar for the cool core size.

central BCG and deposit a large amount of energy into the ambient gas at large radii (e.g. Smith et al. 2002; Lane et al. 2004; Sun, Jerius & Jones 2005; O’Sullivan et al. 2010). The large CCs could be disrupted and transform into the coronae (e.g. Soker 2016). However,

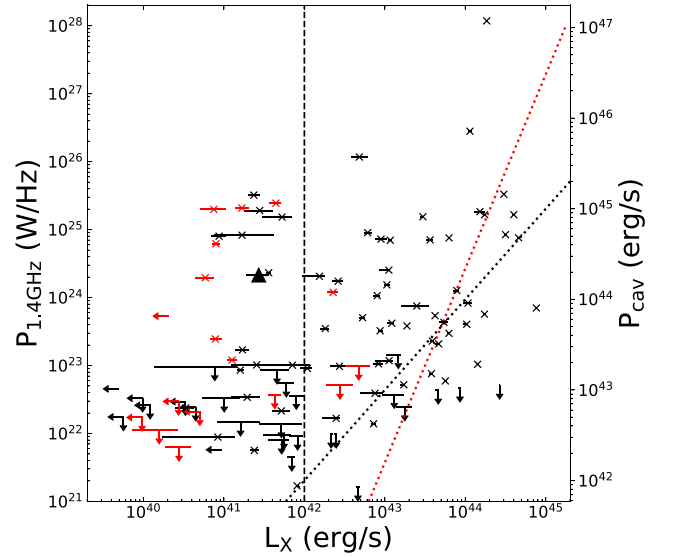


Figure 3. Bolometric X-ray luminosity within the cooling radius versus radio power of the central BCG at 1.4 GHz. The dashed line ($L_{X,\text{bol}} = 10^{42}$ erg s^{-1}) separates the large cool cores and small cool cores. Data points in red are for the systems with large offsets (greater than 50 kpc). The triangle symbol represents the cluster 3C 129.1 (see Section 5). The y-axis on the right is the cavity power estimated using the relation from Cavagnolo et al. (2010). The dotted lines show equality of bolometric X-ray luminosity and cavity power, which is estimated using the relations from Bîrzan et al. (2008) (red dotted line) and Cavagnolo et al. (2010) (black dotted line), respectively.

we did not observe many clusters with strong radio AGNs ($P_{1.4\text{GHz}} > 2 \times 10^{24}$ W Hz^{-1}) while having CC luminosities between 10^{42} and 10^{43} erg s^{-1} , or a CC size between about 10 and 20 kpc in Figs 2 and 3. In fact, there are a total of 17 clusters with $P_{1.4\text{GHz}} > 2 \times 10^{24}$ W Hz^{-1} and with large CCs. The fraction of these clusters decreases with the CC luminosity, e.g. from ~ 47 per cent for clusters with $10^{44} < L_{X,\text{bol}} < 10^{45}$ erg s^{-1} to ~ 24 per cent for clusters with $10^{42} < L_{X,\text{bol}} < 10^{43}$ erg s^{-1} . Therefore, the low fraction of such clusters, with $10^{42} < L_{X,\text{bol}} < 10^{43}$ erg s^{-1} and strong radio AGN, suggests

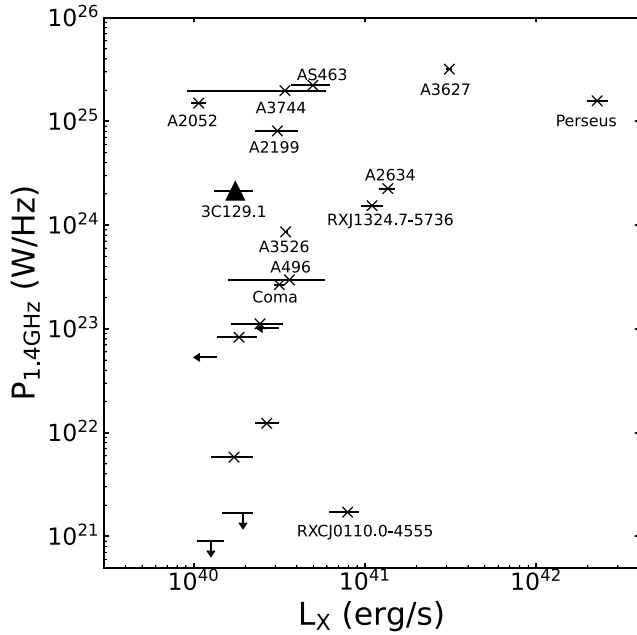


Figure 4. Bolometric X-ray luminosity within 1 kpc versus radio power of the central BCG at 1.4 GHz for clusters within redshift $z < 0.04$ in our sample. The triangle symbol represents the cluster 3C 129.1. There is a lack of clusters with both strong circumnuclear X-ray cool cores ($L_X > 10^{41}$ erg s $^{-1}$) and weak radio AGN ($P_{1.4\text{GHz}} < 10^{24}$ W Hz $^{-1}$).

that if the large CCs can be disrupted by strong radio AGN and turned into the coronae, the time spent during this stage should be short. However, we need to note that the number of clusters in this range is quite small, and there is a possibility that our sample does not have many such clusters by chance. A statistically large, complete cluster sample will help us to check whether our interpretation is true or not.

4.3 Circumnuclear X-ray cool cores

As AGN feeding is a phenomenon happening in the very centre of the BCG, we also explore the relationship between the circumnuclear X-ray luminosity versus the radio luminosity of the BCG (Fig. 4). We defined the circumnuclear X-ray luminosity in this study as the bolometric X-ray luminosity enclosed within 1 kpc of the central BCG. We extracted the source spectrum from a circular region centred on the BCG with a radius of 1 kpc, and the background spectrum within an annulus from 1 to 2 kpc. In order to robustly measure the luminosity within the central 1 kpc, we only studied clusters at $z < 0.04$, where 1 kpc > 1.26 arcsec to be resolved by *Chandra*, and with more than 60 counts in the 0.5–7.0 keV band within 1 kpc after background subtraction for statistical constraints. There are a total of 21 galaxy clusters which satisfy these criteria. To measure the circumnuclear X-ray luminosity, we fitted the spectrum with an absorbed thermal component for the hot gas, and a power-law component to account for the possible non-thermal emission from the central AGN. We found that there are no systems with low radio power ($P_{1.4\text{GHz}} < 10^{24}$ W Hz $^{-1}$) and strong circumnuclear X-ray luminosity ($L_X > 10^{41}$ erg s $^{-1}$). In other words, BCGs with strong circumnuclear X-ray CC ($L_X > 10^{41}$ erg s $^{-1}$) within 1 kpc are always associated with strong radio AGN ($P_{1.4\text{GHz}} > 10^{24}$ W Hz $^{-1}$). This may suggest that high circumnuclear X-ray luminosity in galaxy cluster may be used as a probe of radio AGN. However, this result needs to be examined with a large, representative sample.

Table 5. *Chandra* Observations of 3C 129.1 (PI: Sun).

ObsID	Date Obs	Total Exp (ks)	Cleaned Exp (ks)
19567	2016 Dec 20	15.1	14.3
19965	2016 Dec 21	64.2	63.5

We also estimated the offset between the BCG and the X-ray peak for these 21 clusters. In general, the offsets are relatively small, within 0.6 kpc for all but five clusters in our sample. The largest offset is ~ 2 kpc for the Ophiuchus cluster, whose circumnuclear X-ray luminosity is small, with an upper limit of 1.4×10^{40} erg s $^{-1}$. A high-resolution *Chandra* X-ray image reveals that the peak of cluster CC is displaced from the central BCG, which is probably the reason for the lack of strong AGN activity in both radio and X-ray (Werner et al. 2016). Recently, using low-frequency radio data, Giacintucci et al. (2020) found a giant cavity filled with diffuse radio emission with a steep radio spectrum, which could be due to an extraordinarily powerful past AGN outburst. The steep radial density and temperature gradient of the Ophiuchus CC may help it survive disruption by AGN jets piercing the CC and depositing energy right outside the core. The other three clusters with more than 0.6 kpc offset are 2A0335+096, A496, and AWM7.

5 A DETAILED CASE STUDY OF 3C 129.1

In this section, we present a detailed analysis of a corona system with a strong radio AGN. The 3C 129.1 cluster, with a temperature of ~ 5.6 keV (Ikebe et al. 2002), contains two strong radio sources, i.e. 3C 129 and 3C 129.1. 3C 129.1 (or WEIN 051) is the BCG of this cluster. 3C 129.1 was observed by *Chandra* for 9.5 ksec in 2001 (ObsID 2219). The previous studies showed that the system has a heated core and several candidates of ultraluminous X-ray sources (ULXs) (Krawczynski 2002; Krawczynski et al. 2003). At the very centre, 3C 129.1 hosts a small, extended X-ray source and it is most likely a thermal corona (Sun et al. 2007). In fact, in this work we found the cluster core is heated, with an elevated metal abundance (see Section 5.3), which was proposed to be a signature of a cool core remnant (e.g. Rossetti & Molendi 2010). Here, we used new *Chandra* observations to study this candidate of a CC remnant.

5.1 *Chandra* data analysis

3C 129.1 was observed by *Chandra* for ~ 80 ksec split into two observations (Obs. IDs 1957 and 19965, PI: Sun) in 2016 December with the Advanced CCD Imaging Spectrometer (ACIS). Both observations (Aimpoint on chip S3) were taken in Very Faint (VFAINT) mode and centred on the cool core. The details of the *Chandra* observations are summarized in Table 5. There was one ACIS-I observation taken in 2001 with a short exposure of ~ 9.5 ksec. Another ACIS-S observation was taken in 2000, however, it is centred on the galaxy 3C 129. In this study, we focus on the newer ACIS-S data. The data analysis followed the standard process (see Section 3). To improve background filtering we set `CHECK_VF_PHA` as yes to remove bad events that are likely associated with cosmic rays. We checked that there were no strong background flares for any observations and the resulting cleaned exposure time is shown in Table 5. The CALDB blank sky background was used in our data analysis. We estimated the X-ray sky background residuals using background models including two APEC components with zero redshift and Solar abundance and one power-law component.

The 3C 129.1 cluster lies close to the Galactic plane, so the Galactic absorption is important to our spectral analysis. In our spectral analysis, we allowed the absorption column density to be free (see Appendix A).

5.2 Radio data analysis

The Giant Metrewave Radio Telescope (*GMRT*) observations at 240 and 610 MHz were carried out on 2002 May 19 and May 24, respectively. The data were collected in the standard spectral line mode with a spectral resolution of 125 kHz. The visibility data were converted to FITS and analysed using the NRAO Astronomical Image Processing System package (AIPS) (Lal & Rao 2005). The standard flux density calibration source was observed in the beginning as an amplitude calibrator and also to estimate and correct for the bandpass shape. The phase calibration source was observed once every 35 min. The error in the estimated flux density, both due to calibration and systematic, is less than ~ 5 percent. The data suffered from intermittent radio frequency interference. Thus, in addition to normal editing of the data, the channels affected due to radio frequency interference were identified and edited, after which the central channels were averaged using AIPS task ‘SPLAT’. To avoid bandwidth smearing, 6.75 MHz of clean band at 240 MHz was reduced to six channels of 1.125 MHz each, and 13.5 MHz of clean band at 610 MHz was averaged to give three channels of 4.5 MHz each. While imaging, 49 facets, spread across $\sim 2^\circ \times 2^\circ$ field were used at 240 MHz, and 9 facets covering slightly less than $0.7^\circ \times 0.7^\circ$ field were used at 610 MHz to map each of the two fields using AIPS task ‘IMAGR’. We used ‘uniform’ weighting and the 3D option for ‘W’-term correction throughout our analysis. After 2–3 rounds of phase self-calibration, a final amplitude and phase self-calibration was made to get the final image. At each round of self-calibration, the image and the visibilities were compared to check for the improvement in the source model. The final maps were stitched together using AIPS task ‘FLATN’ and corrected for the primary beam shape of the *GMRT* antennas using AIPS task ‘PBCOR’ (see also Lal et al. 2019). The final image at 240 MHz has a resolution of $13.1 \text{ arcsec} \times 10.8 \text{ arcsec}$ and an rms noise level (1σ) of $1.3 \text{ mJy beam}^{-1}$. The final image at 610 MHz has a resolution of $8.0 \text{ arcsec} \times 7.1 \text{ arcsec}$ and an rms noise level of $0.3 \text{ mJy beam}^{-1}$.

The Very Large Array (VLA) image at 4.76 GHz was downloaded from NRAO VLA archive.³ The observation was taken on 2000 February 8 with B configuration. The image was generated using the VLA pipeline in AIPS. The beam size is 1.25 arcsec and the rms level is $25.1 \text{ } \mu\text{Jy beam}^{-1}$.

The radio images of 3C 129.1, from *GMRT* at 240 and 610 MHz, and VLA at 5 GHz, are shown in Fig. 5. The radio emission of 3C 129.1 is relatively compact with a radio power at 1.4 GHz of $\sim 2 \times 10^{24} \text{ W Hz}^{-1}$.

5.3 Properties of 3C 129.1 ICM and cool core remnant

Fig. 6 (left) shows the combined background-subtracted, exposure-corrected *Chandra* images of 3C 129.1 in the 0.7–4.0 keV band, smoothed by a 10-pixel Gaussian kernel. The central bright region shows the corona with a size of less than 10 kpc. We used unsharp masking to determine the size and position of X-ray cavity. Fig. 6 (middle) shows the unsharp-masked image generated by subtracting the 0.7–4.0 keV background-subtracted, exposure-corrected image

smoothed with 10-pixel Gaussian kernel from the image smoothed with 3-pixel Gaussian kernel. A potential X-ray cavity is shown with the ellipse. We then extracted the azimuthally averaged surface brightness profile and the surface brightness profile in the wedge along the south-western direction. As shown in the inserted figure in the middle panel of Fig. 6, there is a clear surface brightness depression from $\sim 10 - 20 \text{ arcsec}$, corresponding to the position of X-ray cavity. Based on the surface brightness, we calculated the significance of the depression of $\sim 3\sigma$ within the cavity. Fig. 6 (right) is the zoom-in *Chandra* image overlaid with the VLA 5 GHz radio contours. The bright core is a little bit more extended towards the north-east. The X-ray cavity overlaps with the south-western radio lobe.

To obtain temperature profiles, we extracted the spectra from a set of 11 circular annuli centred on the BCG to a radius of $\sim 180 \text{ kpc}$ for two observations using the CIAO tool ‘specextract’. The spectra from the same region from two observations were fitted simultaneously to an absorbed thermal APEC model, i.e. TBABS*APEC, in the energy range 0.5–7.0 keV, with the fixed background models scaled to the extraction area. The temperature, metallicity, and the normalization were allowed to vary freely, as well as the absorption column density. We checked the deprojected temperature within the central cool core region ($< 7 \text{ kpc}$) from the inner three annuli. We extracted one spectrum from the region outside the cool core (from 7 to 180 kpc) for deprojection purpose. We then obtained the deprojected temperature using a model-independent approach (e.g. Dasadia et al. 2016; Liu et al. 2019), which can account for point sources and chip gaps, by fitting the spectrum with an absorbed thermal component and accounting for the emission contribution from the outer spherical shell. Fig. 7 shows the azimuthally averaged radial profiles of the projected temperature and abundance, as well as the deprojected temperature and abundance in the inner $\sim 7 \text{ kpc}$. Since the deprojected abundance cannot be well constrained, we fixed it at the value close to that from projection analysis. With the new deep *Chandra* observation, the temperature profile in the central $\sim 11 \text{ kpc}$ region can be resolved into four data bins. We found the temperature in the innermost bin is $1.17_{-0.14}^{+0.15} \text{ keV}$. The temperature then rises outwards to $4.65_{-0.46}^{+0.57} \text{ keV}$ at $\sim 9 \text{ kpc}$ and remains relatively constant towards $\sim 180 \text{ kpc}$. The abundance profile outside $\sim 7 \text{ kpc}$ follows the general trend found in most of galaxy clusters and it decreases from $1.23_{-0.35}^{+0.43} \text{ Solar}$ abundance to $0.35_{-0.11}^{+0.12} \text{ Solar}$. However, in the central $\sim 7 \text{ kpc}$, the abundance is relatively flat in the central two innermost bins, then rises to a high value of $\sim 3.0 \text{ Solar}$, though with a large error bar. The temperature and abundance profiles suggest that 3C 129.1 is a corona system. The elevated abundance at $\sim 5 \text{ kpc}$ could be due to that the high-abundance gas in the inner region has been pushed outwards.

Fig. 8 shows the profiles of pressure, entropy, and the cooling time for the cluster 3C 129.1. As mentioned in Section 4.1, we obtained the gas density by deprojecting the surface brightness profile. We calculated the pressure as $P = nkT$, the entropy as $S = kT/n_e^{-2/3}$, and the cooling time as $t_{\text{cool}} = \frac{3nkT}{2n_e n_H \Lambda(T, Z)}$, where n is the total number density, n_e and n_H are the electron and proton densities, $\Lambda(T, Z)$ is the cooling function for a given temperature and metal abundance. The entropy in the innermost bin is $\sim 5.5 \text{ keV cm}^2$. Starting from $\sim 2.5 \text{ kpc}$ (the second data bin) the entropy increases suddenly from less than 20 to $\sim 126 \text{ keV cm}^2$ at $\sim 9 \text{ kpc}$ (the fourth data bin). If we fit the entropy in the innermost two data bins and the outermost four data bins with a power law, the entropy in the middle region clearly shows enhancements (e.g. $\sim 70 - 90 \text{ keV cm}^2$ in each data bin within $\sim 7 - 30 \text{ kpc}$), suggesting the gas has been heated. The central cooling time is less than 1 Gyr. The cooling radius, defined as the

³<https://www.vla.nrao.edu/astro/nvas/>

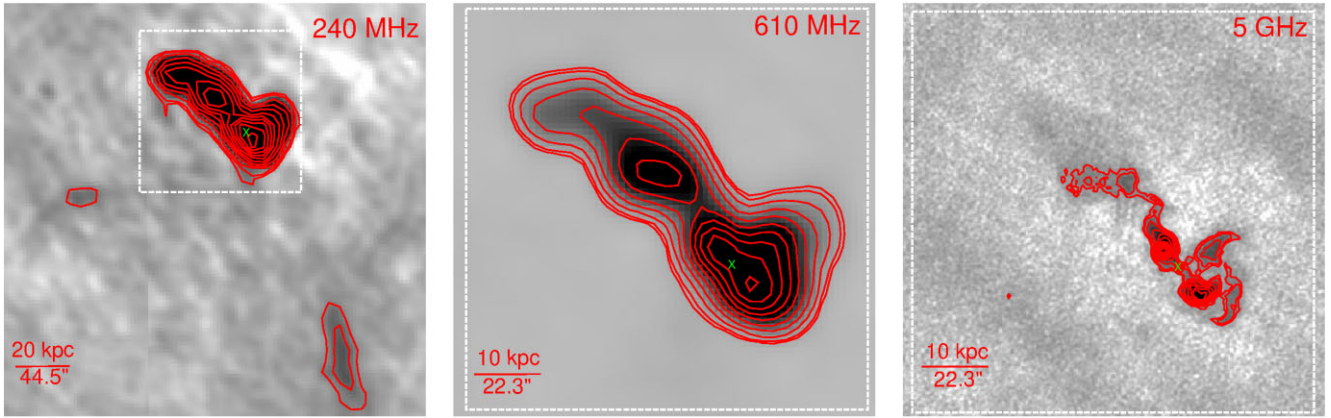


Figure 5. GMRT 240 MHz (left), 610 MHz (middle), and VLA 4.76 GHz (right) images with an rms level of 1300 , 300 , and $25.1 \mu\text{Jy beam}^{-1}$ (1σ) and contours of 3C 129.1. The GMRT 204 and 610 MHz images have a resolution of $13.1 \text{ arcsec} \times 10.8 \text{ arcsec}$ and $8.0 \text{ arcsec} \times 7.1 \text{ arcsec}$, respectively. The beam size of VLA image is 1.25 arcsec . The GMRT 240 MHz contours start from 4σ to 0.4 Jy beam^{-1} . The GMRT 610 MHz contours start from 30σ to 1000σ . The VLA 4.76 GHz contours start from 4σ to 200σ . All contours used the square-root spacing. In the left panel faint diffuse emission is detected to the southwest (~ 2.5 – 4.3 arcmin from the nucleus), and to the southeast (~ 2 – 2.8 arcmin from the nucleus). The green cross indicates the position of the central BCG. The white boxes are the same in all panels with a size of $2.25 \text{ arcmin} \times 2.25 \text{ arcmin}$.

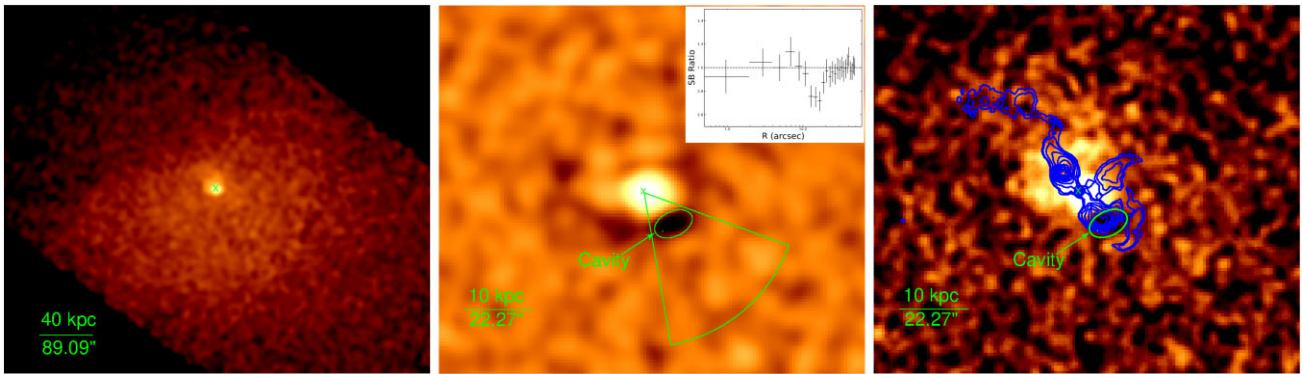


Figure 6. Left: The combined background-subtracted, exposure-corrected *Chandra* images of 3C 129.1 in the 0.7 – 4.0 keV band, smoothed by a 10 -pixel Gaussian kernel. The central bright region is a small cool core. The X-ray point sources have been removed and filled with the local background. Middle: The unsharp-masked image created by subtracting the 0.7 – 4.0 keV background-subtracted, exposure-corrected image smoothed with 10 -pixel Gaussian kernel from the image smoothed with 3 -pixel Gaussian kernel. The ellipse indicates the X-ray cavity. The wedge is used for surface brightness analysis for the detection of the cavity. The inserted image is the ratio of the surface brightness along the wedge to the azimuthally averaged surface brightness. There is a clear surface brightness depression from ~ 10 to $\sim 20 \text{ arcsec}$. Right: The zoomed-in *Chandra* image as in the left panel smoothed with a 3 -pixel Gaussian kernel, overlaid with the VLA 5 GHz radio contours (blue). The contour levels are the same as in Fig. 5. The X-ray cavity overlaps with the radio lobe. The green crosses in all panels indicate the position of the central BCG.

radius where the cooling time is shorter than 4 Gyr , is estimated to be $8.3 \pm 1.1 \text{ kpc}$. We derive an average temperature of $1.6_{-0.25}^{+0.24} \text{ keV}$ and a bolometric luminosity of $2.9 \times 10^{41} \text{ erg s}^{-1}$ within the cooling radius. Assuming the cavity has an ellipsoidal geometry with the projected axis length of ~ 2.9 and $\sim 1.8 \text{ kpc}$ and a distance of $\sim 6.3 \text{ kpc}$ from the nucleus, we estimated a total enthalpy ($H = 4PV$, where P is the azimuthally averaged pressure at the radius of the centre of the cavity) of $\sim 7 \times 10^{56} \text{ erg}$. The buoyant rise time of the bubble is calculated at its terminal velocity $\sim (2gV/SC)^{1/2}$, where V is the volume of the bubble, S is the cross section, $C = 0.75$ is the drag coefficient, and g is the gravitational acceleration (Churazov et al. 2001). Assuming hydrostatic equilibrium and spherical symmetry, we estimated the gravitational acceleration as $g = d\Phi/dr = -\frac{1}{\rho} \frac{dP}{dr}$, where Φ is the gravitational potential, ρ is the density, P is the pressure. We obtained a buoyant rise time of $\sim 10^7 \text{ yr}$ and a cavity power of $\sim 2 \times 10^{42} \text{ erg s}^{-1}$. Based on the $P_{\text{radio}} - P_{\text{cav}}$ relation (e.g. Cavagnolo et al. 2010), the jet power is estimated to be $\sim 10^{44}$

erg s^{-1} , which is much larger than the observed cavity power. This can be due to a few factors. First, any potential cavities at faint regions away from the bright centre can be difficult to be detected with the limited sensitivity of current data. Indeed, the radio lobes at low frequencies are much bigger than the detected X-ray cavities. Secondly, the actual cavity may be larger than the one assumed in the calculation due to the projection effect. Thirdly, old cavities may have already dissipated and mixed with surroundings.

6 DISCUSSION

6.1 Transition of cluster cool cores

Many observational and theoretical studies have suggested that accretion of cold gas fuels AGN feedback in clusters of galaxies (e.g. Pizzolato & Soker 2005; Gaspari, Ruszkowski & Sharma 2012; Gaspari et al. 2013; Li & Bryan 2014; Voit & Donahue 2015;

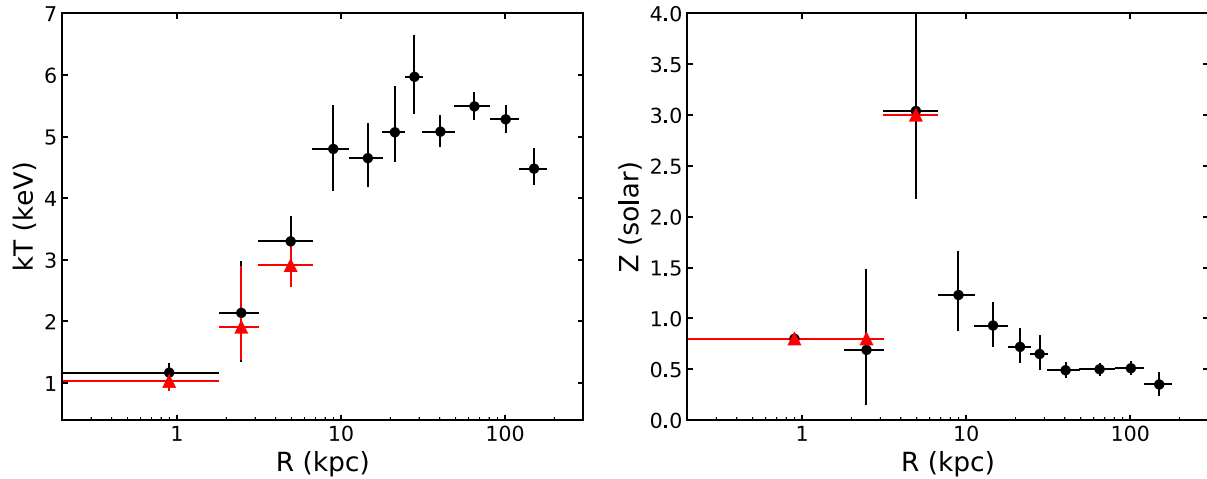


Figure 7. The azimuthally averaged radial profiles of the temperature (left) and abundance (right) of the cluster 3C 129.1. The black circles represent the projected temperature and abundance values, and the red triangles represent the deprojected values.

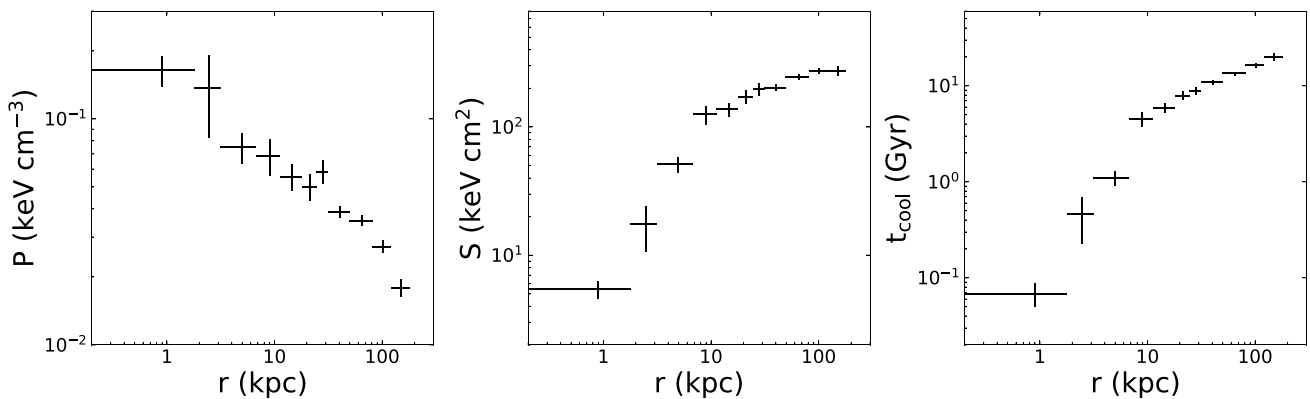


Figure 8. Radial profiles of pressure (left), entropy (middle), and cooling time (right) of the cluster 3C 129.1, after deprojection.

McNamara et al. 2016; Yang & Reynolds 2016; Liu et al. 2019; Wang, Li & Ruszkowski 2019). The accretion rate of the central SMBH can be boosted by orders of magnitude via a process known as CCA/cold gas precipitation, and a large amount of energy can be released through radio jets. In this section, we discuss the possible transitions of cluster CCs due to radio AGN feedback. For illustration, a cartoon plot of cluster CC transitions is shown in Fig. 9. In this study we classify the clusters into two categories, i.e. clusters with the large CC and clusters with the corona, as shown with two ellipses in Fig. 9.

Large CC clusters are in general subject to self-regulated radio AGN feedback. Starting with a large CC cluster with its central SMBH dormant, the hot gas in the X-ray CC cools via top-down multiphase condensation, thus providing the fuelling for the central SMBH through the CCA rain. Once the SMBH ignites and becomes active, it releases a large amount of energy through radio jets that can heat the ICM. Radiative cooling can be suppressed or quenched. The heating process will last until the fuel becomes depleted and the SMBH becomes quiescent again. This standard maintenance mode AGN feedback self-regulated loop in galaxy clusters (e.g. Gaspari & Sądowski 2017) is illustrated with blue arrows in Fig. 9. During this feedback cycle, the radio luminosity of central AGN can increase and decrease, depending on whether the central SMBH is in an active or quiescent state. The CCs can shrink or grow depending

on if it is heated or not by the energy released from the central AGN. For clusters with very large CCs, e.g. A478, A2029, and the Perseus cluster, the central gas pressure and density are very high. It is difficult for the radio jets to penetrate through the high-pressure CCs and deposit a large portion of energy into the outer part of the CCs. We do not expect these very large CCs will change by orders of magnitude.

Although corona systems are different from large CC systems in their CC sizes and luminosities, we take them as different stages of CCs and propose a possible transition scenario for them. Similarly, starting with a large CC cluster with a radio quiet AGN, occasionally, the cluster can have a very powerful AGN outburst (e.g. Li, Ruszkowski & Bryan 2017). If the CC is not too large, the energy released can destroy a large portion of the CC, as long as the radio jet can penetrate through the central region and deposit most of its energy outside, e.g. heat and evacuate the cool gas outside the central 10 kpc. In fact, this can be achieved for a radio AGN as long as (a) the radio jet is very collimated with a small opening angle; (b) there is no relative motion between the jet and ambient gas; (c) the jet is fast with a large Mach number so that the jet can penetrate the central ISM quickly and deposit most of its kinetic energy at large radii (e.g. Soker 2016; Yang, Gaspari & Marlow 2019). In this way the central region of the CC can be kept intact and the corona-like cool cores can be formed. (If the central region of the CC is also

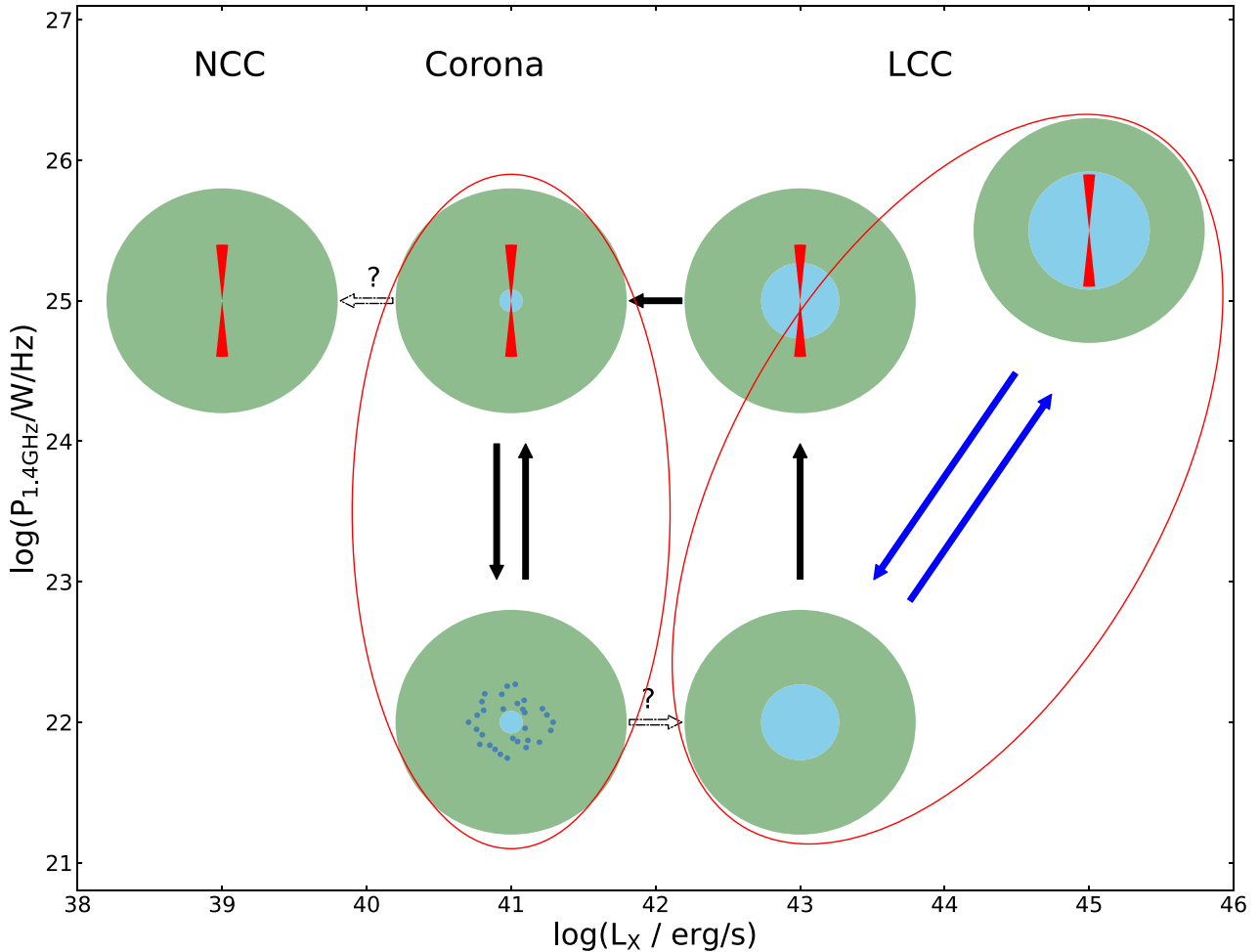


Figure 9. Cartoon plot showing the possible transitions of cluster CCs on the $L_X - P_{\text{radio}}$ plane due to radio AGN feedback in galaxy clusters. Two red ellipses represent corona clusters and large CC clusters. Large CC clusters are subject to self-regulated radio AGN feedback. The radio jets can switch on and off in one AGN feedback loop. This self-regulated AGN feedback loop in large CC clusters is shown as blue arrows on the right. Occasionally, radio quiescent, large CC clusters can have a strong AGN outburst, during which the powerful radio jets penetrate through the inner CC, and deposit a large amount of energy into the outer regions. The CC can be disrupted and turned into a CC remnant or corona (If the CC is totally destroyed, an NCC will be formed). The corona can serve as a mini CC and provide fuel for the central SMBH. Due to the relatively small amount of gas, the central radio AGN fades quickly and becomes radio quiescent. Likely aided by residual cool clumps surviving from the previous heating event, the hot gas outside the central corona can develop local thermal instabilities and cool down, represented by the small blue dots around the central corona. If the gas in the corona continues to feed the central SMBH, the radio AGN may switch on again. Or the corona may cool down, reassemble with the cold clumps, which fall back from outside, and develop into a large CC again. The proposed transitions of large CCs and coroneae are shown in the solid black arrows. Empty arrows with question marks show a possible transition.

heated and disrupted, an NCC cluster may be formed as shown with the empty arrow on the left in Fig. 9.) An example with the similar process is the Cygnus A cluster, whose host galaxy is known as the nearest powerful FR II radio galaxy. The radio jets, cocoon shock, X-ray jets and cavities, and the central source with very bright X-ray emission show the activity of AGN feedback (e.g. Smith et al. 2002; Young et al. 2002; Wilson, Smith & Young 2006; Snios et al. 2018). The radio jets penetrate through the central region with a total projected extend of ~ 130 kpc from west to east. The thermal gas lying within the elliptical cocoon shock exhibits a rib-like structure, which is the debris resulting from the disintegration of the cool core by the radio jets (Duffy et al. 2018). While for the thermal gas close to the nucleus (3 to 6 arcsec, ~ 3.3 – 6.5 kpc from the nucleus), we obtained a temperature of ~ 1.6 keV by masking out the central 3 arcsec region due to the very bright central source, and using a local background from 6 to 9 arcsec region. For the analysis, we followed

the standard *Chandra* data reduction and re-analysed one *Chandra* observation of Cygnus A with ObsID 17512. We fitted the spectrum with an absorbed thermal component plus a power-law component. Although Cygnus A is a large cool core cluster in our sample, it represents an example where the radio jets are heating beyond the central region where there still exists low entropy gas.

The corona of the central BCG can serve as a mini-cool core and continue to provide fuel to the central SMBH. Note that in this process, most of the energy released by central radio AGN should be deposited outside the corona, otherwise, the corona can be destroyed, since the jet power greatly exceeds its cooling luminosity as shown in Fig. 3. However, the corona cannot support radio AGN for very long, as indicated by the fraction of radio strong corona systems in Section 4.1. When the central engine runs out of fuel, the SMBH will shut down and the radio luminosity will eventually drop. Radio strong corona clusters will evolve into radio weak corona systems.

Finally, the central region of the corona also cools down (as discussed in Section 6.3) and provides fuel to the central SMBH. Once the SMBH ignites, the radio AGN will switch on again. Moreover, the X-ray cool core remnants from the previous heating episodes may have residual cool clumps that survived, without raising the X-ray surface brightness much. Without the heating from the central AGN, cooling outside the corona can proceed, aided by the possible residual cool clumps and local thermal instability. Eventually, if the corona can reassemble with the cool gas that falls back from outside, a large CC may be formed again. The possible transitions of large CC and corona systems are shown in the black arrows in Fig. 9.

Simulations have shown that large CCs can be destroyed by high-energy, head-on major mergers and CC clusters can be transformed into NCC clusters (e.g. Hahn et al. 2017). Using binary merging cluster simulations, Valdarnini & Sarazin (2021) found that CCs may be resilient to off-axis mergers with low mass ratios, and CC can survive depending on the initial mass ratios and the angular momentum of the system, as well as in other simulations. One of the important features from a non-zero impact cluster mergers is the gas sloshing (e.g. Markevitch & Vikhlinin 2007), which has been proposed as another heating source (e.g. ZuHone, Markevitch & Johnson 2010). Our results show that most of clusters with large offsets have small cool cores, which suggests that gas sloshing could be an effective way to reduce the size of CCs. For example, the recent X-ray studies of galaxy cluster A119 (cluster in our sample with large offset and small CC) found two cold fronts, possibly associated with large-scale gas sloshing (Watson et al. 2023). In addition, the reduction of CC size may be the joint effect of gas sloshing and AGN feedback (e.g. Rasia et al. 2015). The large-scale gas-sloshing caused by cluster passage can cause a disturbance in the ICM and heat cluster CC. If the central SMBH is triggered during this process, the energy released from the AGN can be deposited in the ICM and the CC will be further disrupted.

6.2 Duty cycle

In our study, we define the duty cycle of radio AGN as the fraction of the time when the galaxy hosts a radio-loud AGN, which is crucial to quantify the importance of the AGN feedback. Previous studies show that the duty cycle of radio galaxies based on their radio power has a dependence on the stellar mass of the host galaxies (e.g. Best et al. 2005, 2007; Shabala et al. 2008). In our sample, we found that the fraction of BCGs with radio-loud AGN in the relaxed, small CC systems is ~ 29 per cent ($P_{1.4\text{GHz}} > 10^{23} \text{ W Hz}^{-1}$). The value is consistent with the value for BCGs with a stellar mass of $\sim 10^{11.5} M_{\odot}$ (e.g. Best et al. 2007), with the same radio power threshold for radio-loud AGN. For the relaxed, large CC clusters, the fraction of BCGs with radio-loud AGN is much larger, with a value of ~ 71 per cent ($P_{1.4\text{GHz}} > 10^{23} \text{ W Hz}^{-1}$). This is consistent with the findings of previous studies that clusters with strong CCs tend to host a central radio luminous source (e.g. Burns 1990; Mittal et al. 2009). Recently, using the *GMRT*, Kolokythas et al. (2018) studied a complete sample of local groups with high-richness and found a high radio-detection rate of 92 per cent. Gressová et al. (2022) presented Karl G. Jansky Very Large Array radio observations of a sample of the 42 nearest optically and X-ray brightest early-type galaxies, and found 41 of 42 galaxies have radio detections. But if we take the same radio power threshold (i.e. $P_{1.4\text{GHz}} > 10^{23} \text{ W Hz}^{-1}$), the fractions of galaxies that are radio-loud in these two studies decreases to ~ 11 per cent and ~ 26 per cent, respectively. Moreover, using a complete sample of clusters, Bîrzan et al. (2012) found that the duty cycle for radio-

mode feedback is at least 63 per cent, which is slightly smaller than the fraction of BCGs with radio-loud AGN (71 per cent for $P_{1.4\text{GHz}} > 10^{23} \text{ W Hz}^{-1}$) in our large CC clusters. However, we should note that the duty cycle for radio-mode feedback used in their study is the fraction of the time when a cluster possesses bubbles inflated by the central radio source.

In addition, during the life-cycle of a radio AGN, it experiences different phases, e.g. from a young, newly born radio source to an evolved radio source, then to the remnant phase when AGN activity stops, and to a restarted phase when the central AGN is active again. The radio morphology and spectra contain essential information about the radio sources and can be used to identify which phase the radio source is currently in. Using a method combining spectral ageing and dynamical models, Turner (2018) studied the galaxy group B2 0924+30 with the remnant and restarted radio-loud AGN to constrain its duty cycle, which is defined as $t_{\text{on}}/(t_{\text{on}} + t_{\text{off}})$, where on and off represent the radio jet being switched on and off. Note that the paper did not give a quantitative radio power threshold corresponding to the active and quiescent stages, because in the spectral ageing model including radio source evolution, the radio luminosity is a function of both the age of radio source and jet power, and a low-powered source can maintain its luminosity long after the jet is switched off. In their study, the remnant AGN is found to have an active age of 50 Myr and a total age of 78 Myr, corresponding to a duty cycle of ~ 64 per cent. However, if considering a previous AGN outburst in the model, they found that the time between two outbursts is at least 330 Myr. Therefore, the duty cycle of remnant B2 0924+30 is less than 15 per cent. Biava et al. (2021) used new LOFAR observations at 144 MHz together with archival radio data at higher frequencies to investigate the spectral properties of galaxy cluster MS 0735.6+7421, which has one of the most powerful known AGN and two pairs of X-ray cavities (e.g. Vantyghem et al. 2014). Similarly, by fitting the lobe spectra but using a single particle injection model, they derived the spectra ages for outer and intermediate lobes, which represent different jet episodes. They found that the two episodes of jet activity are separated by a brief quiescent phase and the duty cycle is close to unity.

Based on the fractions of BCGs with radio-loud AGN, the duty cycle for small CC clusters is less than half of that for large CC clusters. This suggests that the radio activity of BCGs is affected by the properties of the surrounding gas beyond the central ~ 10 kpc. Strong radio AGNs in small X-ray CCs fade more rapidly than those embedded in large X-ray CCs. However, it is not very clear what causes this difference in duty cycle in the small and large CC systems, and if the difference is related to the available amount of cold gas serving as the fuel for the central SMBH. A detailed study of the inventory of cold/warm gas in corona systems will provide essential information to answer this question.

6.3 Heating in the cool core coronae

Another interesting question is how a corona system can maintain its steady state. As shown in Fig. 3, the cavity power estimated from the radio luminosity for corona systems is much larger than the cooling luminosity. Therefore, most of the energy released from radio AGN must be deposited into the ICM outside the central corona, which can be achieved in certain conditions (e.g. Soker 2016). In addition, the total heat flux across the surface of a cool corona surrounded by a hot ICM can be estimated as $8.2 \times 10^{42} (T/5 \text{ keV})^{3/2} (n_{\text{ICM}}/10^{-3} \text{ cm}^{-3}) (r/3 \text{ kpc})^2 \text{ ergs s}^{-1}$ based on the saturated conductive heat flux in Cowie & McKee (1977), which is much larger than the X-ray luminosity of corona (e.g. see table

3) within a typical hot cluster. Therefore, the thermal conductivity is required to be significantly reduced for the survival of cool core coronae (e.g. Vikhlinin et al. 2001; Sun et al. 2007). In this way, the central corona can serve as a steady small cooling flow and fuel the central SMBH without disruption. However, if the energy released from the central radio AGN is used to heat the IGM or ICM at large radii, there should be another heating source to balance the cooling. Voit et al. (2020) proposed a black-hole feedback valve mechanism, in which SNe heating in galaxies with a large central velocity dispersion can lead to a quasi-steady state with a modest cooling flow at small radii, while AGN feedback appears to regulate the CGM pressure or heat the ICM (e.g. see review in Donahue & Voit 2022).

Here we consider the requirements on SNe feedback, such as the heating from explosions of white-dwarf SNe (SNIa) to balance the cooling within the central coronae. Sun et al. (2007) found that the SNe inside the coronae generally have enough energy to balance cooling, although the required fraction of the SNe energy required to be deposited into the coronal gas increases with the galaxy's luminosity. We adopted the same SNe rate in early-type galaxies (Cappellaro, Evans & Turatto 1999), $0.166h_{70}^2$ per 100 yr per $10^{10} L_{B\odot}$, and assumed a kinetic energy of 10^{51} erg per SN. For a stellar population of age ~ 10 Gyr and a stellar mass of $\sim 10^{11.5} M_{\odot}$, the SNIa kinetic power is $\sim 2 \times 10^{41}$ erg s^{-1} , assuming a stellar mass-to-light ratio of 10 in the B -band for early-type galaxies (e.g. Faber & Gallagher 1979; Nagino & Matsushita 2009). A recent study showed that the observed SNIa rate for a stellar population among elliptical galaxies in galaxy clusters is $\sim 3 \times 10^{-14}(t/10 \text{ Gyr})^{-1.3} \text{ yr}^{-1} M_{\odot}^{-1}$ (Friedmann & Maoz 2018). Using the updated SNIa rate, we obtained the SNIa feedback power of $\sim 3 \times 10^{41}$ erg s^{-1} . Since the dividing X-ray bolometric cooling luminosity for large CCs and coronae is $\sim 10^{42}$ erg s^{-1} (the conversion factor from 0.5–2 keV luminosity to bolometric luminosity for low-temperature corona gas is ~ 2), the SNIa heating is enough to balance the cooling for many corona systems, as long as the energy of SNIa can be efficiently coupled into the corona gas. However, the SNe heating should follow the stellar light profile, which is shallower than the X-ray emission profile of coronae (e.g. Sun et al. 2007). Thus, it can be challenging to match SN heating and cooling spatially, so a corona may still cool around the nucleus and provide fuel for the central SMBH.

7 CONCLUSION

In this paper, we used a large sample of 108 nearby clusters ($z < 0.1$) with $kT > 3$ keV to study the effect of AGN heating and the transitions of cluster CCs. The main conclusions are the following.

(i) For galaxy clusters with small offsets (< 50 kpc) between the central BCG and the X-ray cluster centre, about 40 per cent of them have small CCs. While for clusters with large offsets, most of them (14 out of 17) have small CCs. This suggests that cluster mergers or sloshing are efficient in reducing the CC size.

(ii) Using the CC size or CC luminosity to classify small and large CCs gives consistent results. Large CC clusters generally show a weak correlation between the CC luminosity and the radio luminosity. The inferred kinetic power, estimated on the basis of the $P_{\text{radio}} - P_{\text{cavity}}$ relation, generally exceeds the CC luminosity. Small CC clusters do not show such a correlation, and the inferred kinetic power could greatly exceed the CC luminosity.

(iii) In clusters with large offsets, the fraction of radio strong systems ($P_{1.4\text{GHz}} > 10^{23} \text{ W Hz}^{-1}$) is ~ 53 per cent. In clusters with small offsets, large CC systems show a relatively continuous dis-

tribution of radio power, while small CC systems are mostly radio weak (71 per cent for $P_{1.4\text{GHz}} < 10^{23} \text{ W Hz}^{-1}$). Furthermore, there is a lack of small CC clusters with intermediate radio power of $2 \times 10^{23} - 2 \times 10^{24} \text{ W Hz}^{-1}$. This suggests different radio AGN feedback processes in large and small CC clusters. The radio AGN stage is more continuous in large CCs, while in small CCs, the radio AGNs spend a much shorter time in radio strong stage.

(iv) We estimated the circumnuclear X-ray luminosities, within 1 kpc of the BCGs, and found that there are no systems with low radio power ($P_{1.4\text{GHz}} < 10^{24} \text{ W Hz}^{-1}$) while having a strong circumnuclear X-ray luminosity ($L_X > 10^{41} \text{ erg s}^{-1}$).

(v) We presented a detailed study of the galaxy cluster 3C 129.1. The small central cooling time, low central entropy, abundance bump, and elevated entropy profile outside the central core ($> \sim 9$ kpc) suggest that it is a CC remnant, possibly disrupted by a radio AGN outburst.

(vi) We outlined the evolutionary transitions that cluster cores may undergo in their thermal states. Clusters with luminous CCs are subject to a self-regulated feedback cycle. If, occasionally, the radio AGN outburst is very powerful, the collimated radio jets can penetrate the central part of CC and deposit a large amount of energy outside (e.g. Soker 2016; Yang et al. 2019). In this way, a large portion of the CC can be disrupted and a corona class object can be formed with the gas outside the central ~ 10 kpc being heated and evacuated. However, the corona cannot support radio AGN for very long, and the radio luminosity of the central BCG fades quickly once the SMBH is out of fuel. If the hot gas in the corona can cool and fuel the central SMBH, its radio activity can be enhanced again. Outside of the central corona, if there are residual cool clumps surviving from the previous heating episode, they may grow by cooling and may also rain down towards the central corona to increase the cool core size.

(vii) Based on the fraction of BCGs with radio strong AGN, we found that the duty cycle in relaxed, small CC clusters is ~ 29 per cent ($P_{1.4\text{GHz}} > 10^{23} \text{ W Hz}^{-1}$), while the duty cycle for large CC clusters is ~ 71 per cent, respectively. The low duty cycle in small CC clusters suggests that the radio activity of BCGs is affected by the properties of the surrounding gas beyond the central ~ 10 kpc, and strong radio AGN in small X-ray CCs fade more rapidly than those embedded in large X-ray CCs. However, the origin of the different duty cycles between small CC clusters and large CC clusters is unclear. Detailed studies on the inventory of cold/warm gas in corona systems will help us to address this question.

This study used data carefully collected from the *Chandra* archive, but it is still limited by the detection ability of current X-ray instruments, e.g. we have to set a redshift limit of 0.1 in order to resolve the gas properties in the central region of galaxy cluster. Future X-ray missions with larger collecting power and better spatial resolution will help us to observe more corona systems at low and higher redshift and to study their properties and cool core transitions.

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DATA AVAILABILITY

The *Chandra* raw data used in this paper are available to download at the HEASARC Data Archive website (<https://heasarc.gsfc.nasa.gov/docs/archive.html>). The reduced data underlying this paper will be shared on reasonable requests to the corresponding authors. This research has made use of software provided by the Chandra X-ray Center (CXC) in the application package CIAO.

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APPENDIX A: ABSORPTION COLUMN DENSITY

Since the cluster 3C 129.1 lies close to the Galactic plane, the Galactic absorption is high and its accurate value is essential for our spectral analysis. We examined the X-ray absorption column density towards 3C 129.1. The weighted column density of the total Galactic hydrogen, including both the atomic hydrogen and molecular hydrogen, is $7.36 \times 10^{21} \text{ cm}^{-2}$, calculated using the ‘Nhtot’ tool⁴ (Willingale et al. 2013). We then checked the nH profile by

⁴<http://www.swift.ac.uk/analysis/nhtot/index.php>

fitting the spectra extracted from several annular regions centred on the cluster 3C 129.1 from two new ACIS-S observations. The model includes an absorbed thermal component for the diffuse emission from the cluster plus the diffuse X-ray background component. The background was modelled and re-scaled based on the local X-ray background estimate. The absorption column density, temperature, abundance, and normalization of the cluster emission were allowed to vary. We plotted the best-fitting values of the absorption column density in Fig. A1. The absorption column density in the central 10 arcsec is consistent with the weighted column density of the total Galactic hydrogen. It then rises quickly to a high value of $\sim 1.2 \times 10^{22} \text{ cm}^{-2}$ and becomes relatively flat outside the central 10 arcsec.

In our analysis, we tried both fixing the absorption column density at the weighted value of $7.36 \times 10^{21} \text{ cm}^{-2}$, and letting it vary freely. We found that freeing the column density in the spectral fitting gives a much lower C-statistic. Therefore, in the text we show the result obtained from spectral fitting with free absorption column densities for 3C 129.1.

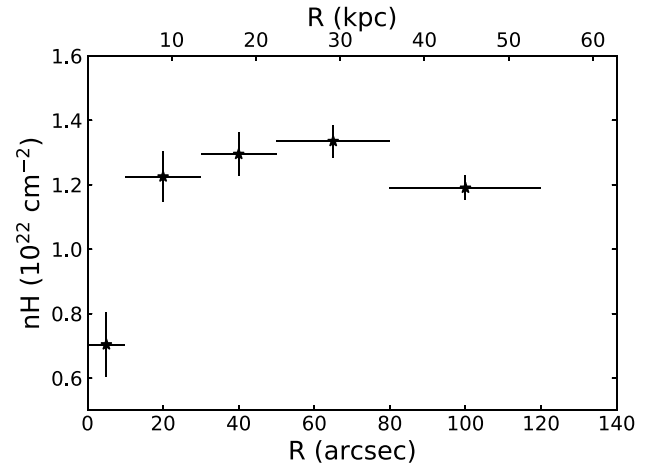


Figure A1. The fitted absorption column density as a function of radius for the 3C 129.1 cluster.

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